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# Guide to the Disposal of Chemically Stabilized and Solidified Waste

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# Guide to the Disposal of Chemically Stabilized and Solidified Waste

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Phil Malone, Larry Jones

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The "Guide to the Disposal of Chemically Stabilized and Solidified Wastes" provides guidance to waste generators and regulatory officials in the use of chemical stabilization/solidification techniques for limiting hazards posed by toxic wastes in the environment. The current state and performance of hazardous waste disposal and long-term storage techniques are discussed. In addition to a discussion of major chemical and physical properties of treated wastes, a list of major stabilization/solidification technology suppliers and a summary of each process are provided.

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# GUIDE TO THE DISPOSAL OF CHEMICALLY STABILIZED AND SOLIDIFIED WASTE

by

Environmental Laboratory
U.S. Army Engineer Waterways Experiment Station
Vicksburg, Mississippi 39180

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Project Officer

Robert E. Landreth
Solid and Hazardous Waste Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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# FOREWORD

The Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of the environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is the first necessary step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and the solid and hazardous waste pollutant discharges from municipal and community sources; to preserve and treat public drinking water supplies; and to minimize the adverse economic, social, health and aesthetic effects of pollution. This publication is one of the products of that research--a vital communications link between the researcher and the user community.

This study examines procedures for the treatment of hazardous industrial wastes for disposal, including physical and chemical test procedures and outlines options for ultimate disposal of treated wastes. Techniques that solidify or chemically stabilize industrial waste products may contribute to the preservation of human health and the environment by helping us immobilize and isolate toxic materials.

FRANCIS T. MAYO
Director
Municipal Environmental Research
Laboratory

# PREFACE

The land disposal of hazardous waste is subject to the requirements of Subtitle C of the Resource Conservation and Recovery Act of 1976. This Act requires that the treatment, storage, or disposal of hazardous wastes after November 19, 1980, be carried out in accordance with a permit. The one exception to this rule is that facilities in existence as of November 19, 1980 may continue operations until final administrative disposition is made of the permit application (providing that the facility complies with the Interim Status Standards for disposers of hazardous waste in 40 CFR Part 265). Owners or operators of new facilities must apply for and receive a permit before beginning operation of such a facility.

The Interim Status Standards (40 CFR Part 265) and some of the administrative portions of the Permit Standards (40 CFR Part 264) were published by EPA in the Federal Register on May 19, 1980. EPA will soon publish technical permit standards in Part 264 for hazardous waste disposal facilities. These regulations will ensure the protection of human health and the environment by requiring evaluations of hazardous waste management facilities in terms of both site-specific factors and the nature of the waste that the facility will manage.

The permit official must review and evaluate permit applications to determine whether the proposed objectives, design, and operation of a land disposal facility will be in compliance with all applicable provisions of the regulations (40 CFR 264).

EPA is preparing two types of documents for permit officials responsible for hazardous waste landfills, surface impoundments, and land treatment facilities: Permit Writers Guidance Manuals and Technical Resource Documents. The Permit Writers Guidance Manuals provide guidance for conducting the review and evaluation of a permit application for site-specific control objectives and designs. The Technical Resource Documents support the Permit Writers Guidance Manuals in certain areas (i.e. liners, leachate management, closure, covers, water balance) by describing current technologies and methods for evaluating the performance of the applicant's design. The information and guidance presented in these manuals constitute a suggested approach for review and evaluation based on best engineering judgments. There may be alternative and equivalent methods for conducting the review and evaluation. However, if the results of these methods differ from those of the EPA method, their validity may have to be validated by the applicant.

In reviewing and evaluating the permit application, the permit official must make all decisions in a well defined and well documented manner. Once an initial decision is made to issue or deny the permit, the Subtitle C regulations (40 CFR 124.6, 124.7 and 124.8) require preparation of either a statement of basis or a fact sheet that discusses the reasons behind the decision. The statement of basis or fact sheet then becomes part of the permit review process specified in 40 CFR 124.6-124.20.

These manuals are intended to assist the permit official in arriving at a logical, well-defined, and well-documented decision. Checklists and logic flow diagrams are provided throughout the manuals to ensure that necessary factors are considered in the decision process. Technical data are presented to enable the permit official to identify proposed designs that may require more detailed analysis because of a deviation from suggested practices. The technical data are not meant to provide rigid guidelines for arriving at a decision. References are cited throughout the manuals to provide further guidance for the permit official when necessary.

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→ Also examined are

## ABSTRACT

Stabilization/solidification of industrial waste is a pretreatment process that has been proposed to insure safe disposal of wastes containing harmful materials. This manual examines the regulatory considerations, current and proposed technology, testing procedures and design of landfills, and other options involved in disposal systems using stabilization/solidification of wastes. A summary of the major physical and chemical properties of treated waste is presented. A listing of major suppliers of stabilization/solidification technology and a summary each process is included.

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# SECTION 1

# INTRODUCTION

## 1.1 PURPOSE

The purpose of this manual is to provide guidance in the use of chemical stabilization/solidification techniques for limiting hazards posed by toxic wastes in the environment, and to assist in the evaluation of permit applications related to this disposal technology. The document addresses the treatment of hazardous wastes for disposal or long-term storage and surveys the current state and effectiveness of waste-treatment technology. This guide provides the background information needed for waste generators and regulatory officials to determine the testing program and/or product information necessary for them to make the best engineering judgments concerning the long-term effectiveness in site-specific conditions.

The manual assumes the permit writer and/or other readers are familiar with the latest regulations concerning the disposition and disposal of hazardous and nonhazardous bulk-liquid and semisolid sludges and wastes in secure and sanitary landfills. Some familiarity with general soil characteristics, water balance, climatic conditions, and fundamentals of leachate generation would also be helpful to the manual user.

## 1.2 THE TERMINOLOGY OF WASTE SOLIDIFICATION/STABILIZATION

The current interest in the technology of waste stabilization/solidification in this country reflects recent social and political priorities placed on environmental protection. Current terminology in the field includes new terms and terms borrowed from other fields which are given new and specific meanings. As a matter of necessity, the following terms are used in this manual with the meanings as noted below. These words have not been officially defined by EPA as have those appearing in the glossary at the end of the manual.

"Solidification" and "stabilization" as used here both refer to treatment systems which are designed to accomplish one or more of the following: (a) improve handling and physical characteristic of the waste, (b) decrease the surface area across which transfer or loss of contained pollutants can occur, (c) limit the solubility of, or to detoxify, any hazardous constituents contained in the wastes. Solidification implies that these results are obtained primarily, but not necessarily exclusively, via the production of a monolithic block of treated waste with high structural integrity. Stabilization techniques are those which have their beneficial action primarily by limiting the solubility or by detoxifying the waste contaminants even though the physical characteristics of the waste may or may not be changed and improved. Stabilization usually involves addition of materials that ensure the hazardous constituents are maintained in their least soluble and/or toxic form.

The term "fixation," has fallen in and out of favor but is widely used in the waste treatment field as generally meaning any treatment system which solidifies and/or stabilizes the waste as just described above. This is the restricted use of the term as it is employed in this document. Other derivatives of this term such as "to fixate" (or "fixated" waste), to "fix" (or "fixed" waste), and even "fixalated" are not used in this manual.

The term "treatment" has been legally defined by the EPA. The EPA has taken the broadest meeting of the term including any method of modifying the chemical, biological, and/or physical character or composition of a waste (see Glossary). Table 1-1 lists the types of treatment processes and their EPA identification numbers which are used in the manifest system. As seen from the listing, treatment includes a wide array of specific techniques; but neither solidification nor stabilization is included. Chemical fixation (T21) is listed under chemical treatment but is not specifically defined. The chemical fixation category is the one under which all treatment processes discussed in this document would fall except for the encapsulation techniques for which a separate category is listed under physical methods (T39). Table 1-2 lists some of the attributes of commonly-available, hazardous waste treatment processes. Note that different types of treatment fulfill different functions on different forms and types of wastes. Many processes in Table 1-2 result only in volume reduction or waste separation and thus still require solidification and stabilization of the waste prior to ultimate disposal.

"Surface encapsulation" as used here is a technique of waste treatment involving isolation of the waste material by placing a jacket or membrane of impermeable, chemically inert material between the waste and the environment. Ideally the jacket is bonded to the external surface of a solidified waste. Encapsulation of small particles is sometimes called "microencapsulation," but this term is used by processors to describe a wide array of different techniques and therefore has no specific meaning.

## 1.3 LEGISLATIVE BACKGROUND

The Resource Conservation and Recovery Act (RCRA) of 1976 (PL 94-580) established a national hazardous waste regulatory program. This law is the most comprehensive attempt to date at guaranteeing the secured disposal of materials that could represent potential threats to human health and the environment. The Act includes provisions for developing criteria to determine which wastes are hazardous, instituting a manifest system, and establishing standards for siting, design, and operation of disposal facilities. The Act encourages the States to conduct their own regulatory programs, but it authorizes the U. S. Environmental Protection Agency (EPA) to administer

TABLE 1-1. TREATMENT CODES FOR EPA HAZARDOUS WASTE MANIFESTS

| EPA Code # | Treatment | EPA Code # | Treatment |
|---|---|---|---|
| (a) | Thermal Treatment | (2) | Removal of Specific Components |
| T06 | Liquid injection incinerator | T48 | Absorption-molecular sieve |
| T07 | Rotary kiln incinerator | T49 | Activated carbon |
| T08 | Fluidized bed incinerator | T50 | Blending |
| T09 | Multiple hearth incinerator | T51 | Catalysis |
| T10 | Infrared furnace incinerator | T52 | Crystallization |
| T11 | Molten salt destructor | T53 | Dialysis |
| T12 | Pyrolysis | T54 | Distillation |
| T13 | Wet air oxidation | T55 | Electrodialysis |
| T14 | Calcination | T56 | Electrolysis |
| T15 | Microwave discharge | T57 | Evaporation |
| T16 | Cement kiln | T58 | High gradient magnetic separation |
| T17 | Lime kiln |  |  |
| T18 | Other (specify) | T59 | Leaching |
| (b) | Chemical Treatment | T60 | Liquid ion exchange |
| T19 | Absorption mound | T61 | Liquid-liquid extraction |
| T20 | Absorption field | T62 | Reverse osmosis |
| T21 | Chemical fixation | T63 | Solvent recovery |
| T22 | Chemical oxidation | T64 | Stripping |
| T23 | Chemical precipitation | T65 | Sand filter |
| T24 | Chemical reduction | T66 | Other (specify) |
| T25 | Chlorination | (d) | Biological Treatment |
| T26 | Chlorinolysis | T67 | Activated sludge |
| T27 | Cyanide destruction | T68 | Aerobic lagoon |
| T28 | Degradation | T69 | Aerobic tank |
| T29 | Detoxification | T70 | Anaerobic lagoon |
| T30 | Ion exchange | T71 | Composting |
| T31 | Neutralization | T72 | Septic tank |
| T32 | Ozonation | T73 | Spray irrigation |
| T33 | Photolysis | T74 | Thickening filter |
| T34 | Other (specify) | T75 | Trickling filter |
| (c) | Physical Treatment | T76 | Waste stabilization pond |
| (1) | Separation of components | T77 | Other (specify) |
| T35 | Centrifugation | T78-79 | (Reserved) |
| T36 | Clarification |  |  |
| T37 | Coagulation |  |  |
| T38 | Decanting |  |  |
| T39 | Encapsulation |  |  |
| T40 | Filtration |  |  |
| T41 | Flocculation |  |  |
| T42 | Flotation |  |  |
| T43 | Foaming |  |  |
| T44 | Sedimentation |  |  |
| T45 | Thickening |  |  |
| T46 | Ultrafiltration |  |  |
| T47 | Other (specify) |  |  |

NOTE: Taken from reference 1-1.

TABLE 1-2. SOME ATTRIBUTES OF COMMONLY AVAILABLE WASTE TREATMENT OPTIONS*

| Process | Functions Performed† | Types of Waste‡ | Forms of Waste | Resource Recovery Capability |
|---|---|---|---|---|
| (a) Thermal treatment: | | | | |
| Pyrolysis | VR,De | 3,4,6 | S,L,G | Yes |
| Incineration | De,Di | 3,5,6,7,8 | S,L,G | Yes |
| (b) Chemical treatment: | | | | |
| Calcination | VR | 1,2,5 | L | |
| Ion exchange | VR,Se,De | 1,2,3,4,5 | L | Yes |
| Neutralization | De | 1,2,3,4 | L | Yes |
| Oxidation | De | 1,2,3,4 | L | |
| Precipitation | VR,Se | 1,2,3,4,5 | L | Yes |
| Reduction | De | 1,2, | L | |
| (c) Physical treatment: | | | | |
| Carbon sorption | VR,Se | 1,3,4,5 | L,G | Yes |
| Dialysis | VR,Se | 1,2,3,4 | L | Yes |
| Electrodialysis | VR,Se | 1,2,3,4,6 | L | Yes |
| Evaporation | VR,Se | 1,2,5 | L | Yes |
| Filtration | VR,Se | 1,2,3,4,5 | L,G | Yes |
| Flocculation/settling | VR,Se | 1,2,3,4,5 | L | Yes |
| Reverse osmosis | VR,Se | 1,2,4,6 | L | Yes |
| Ammonia stripping | VR,Se | 1,2,3,4 | L | Yes |
| (d) Biological treatment: | | | | |
| Activated sludges | De | 3 | L | No |
| Aerated lagoons | De | 3 | L | No |
| Waste stabilization ponds | De | 3 | L | No |
| Trickling filters | De | 3 | L | No |

* Modified from reference 1-3.

† Functions: VR, volume reduction; Se, separation; De, detoxification; Di, disposal.

‡ Waste types: 1, inorganic chemical without heavy metals; 2, inorganic chemical with heavy metals; 3, organic chemical without heavy metals; 4, organic chemical with heavy metals, 5, radiological; 6, biological; 7, flammable; and 8, explosive.
Waste forms: S, solid; L, liquid; and G, gas.

the program until suitable State programs are established. Should a State choose not to develop a hazardous waste program or not to gain approval and authorization for a program, EPA must administer the program in its stead.

Regulations have now been promulgated under the RCRA that direct the generation, handling, treatment, and safe disposal of hazardous and nonhazardous wastes. Legal definitions of what is hazardous and of what constitutes safe disposal have been developed (1-1).

The RCRA augments and overlaps in some areas the authority delegated to the agency in other legislation. Previous legislation had addressed the problem of hazardous waste disposal indirectly by regulating the effects of waste disposal on surrounding air and water quality.

The Federal Water Pollution Control Act, as amended in 1972 (PL 92-500), and the Clean Water Act of 1977 (PL 95-217) direct the establishment of an effluent permit plan for municipalities and industries, but, then do not specifically regulate discharges from solid or hazardous waste disposal activities. However, in regional water quality planning (Section 208 of the PL 92-500), any plan prepared must include a process to control the dispersal of pollutants on land and in subsurface excavations to protect the ground and surface waters. Technically, waste disposal would be controlled indirectly by enforcing a regional plan to insure ground and surface water quality.

Under the Safe Drinking Water Act of 1974 (PL 93-523), the EPA Administrator is charged in Section 1442 with controlling subsurface emplacement of waste. The broad goal of this section is to discover and control potential threats to the quality of groundwater. This Act is the basis for regulations on the subsurface injection of liquid waste and for surface impoundments. An impoundment is defined as a natural depression, artificial excavation, or diked enclosure used for storage, treatment, or disposal of wastes in the form of liquids, semisolids, or solids. In its broadest interpretation, the Safe Drinking Water Act overlaps and reinforces the RCRA.

The Toxic Substances Control Act of 1976 (PL 94-469) established as national policy that data should be developed on the effects of the manufacture, use, and disposal of chemical substances on health and the environment. The EPA administrator is empowered to prohibit or otherwise regulate any manner or method of disposal of a toxic substance by its manufacturer or by any person who uses or disposes of a toxic chemical in a commercial operation. This provision includes all disposal of toxic substances on the land or in landfills or impoundments. The administrator is authorized to take action against persons disposing of a toxic chemical in any manner posing an unreasonable risk to health and the environment.

The Occupational Safety and Health Act of 1970 specified the maximum permissible exposure limits for volatile, hazardous chemicals in the work place. Criteria established under this legislation have been adopted for the disposal of hazardous industrial chemicals that pose a risk for airborne contamination. Under the RCRA and related legislation, the EPA is now responsible for all phases of hazardous waste disposal.

Solidification/stabilization options are treated indirectly in these regulations. For example, rules for landfilling waste (1-1) state that "liquids be modified and/or treated to a non-flowing consistency prior to landfilling or in situ." No solidification requirement beyond this is formally required. Stabilization or chemical binding to prevent loss of toxic constituents, is mentioned in a relation to the effect to be obtained, not as a specific system to be required. The rules state treatment renders the waste "...nonhazardous, safer to transport,..." No specific treatment systems are indicated (1-1). The performance in hazard reduction is the important factor in selecting or requesting stabilization of toxic wastes. This approach encourages inventiveness and allows for flexibility in disposal systems (1-2).

## 1.4 CHARACTERISTICS OF WASTES FOR WHICH STABILIZATION/SOLIDIFICATION ARE EFFECTIVE AND ECONOMICAL

Not all wastes justify treatment. The practical and economic decision concerning which wastes should or should not be submitted to expensive treatment systems is based upon an overall consideration of the amount, composition, physical properties, location, and disposal problems associated with the specific waste. Also of importance is the proven effectiveness and the costs associated with the commercially available treatment systems which are applicable to the specific wastes in question. Wastes which are designated as hazardous by the EPA and are produced in large amounts, are those most commonly considered for solidification and/or stabilization. Thus, the treatment of high volume hazardous waste forms the bulk of the discussion in this manual.

Some types of legally non-hazardous wastes also benefit from treatment processes which would render the waste more easily handled or less likely to lose undesirable constituents to the local groundwater. For instance, flue gas cleaning sludges, although specifically exempted as nonhazardous solid waste by EPA (1-1), have been the subject of a number of solidifications/stabilization studies since their run-off water and leachates are typically high in calcium (600-800 ppm) and sulfate (1200-1500 ppm) and represent a significant threat to the local groundwater even if no heavy metals are present (1-3). Other wastes, whose disposal might benefit from treatment are: mining overburden returned to the mining site; fly ash, bottom ash, and slag wastes; flue gas emission control wastes generated from the burning of fossil fuels; and oil, gas, or geothermal drilling fluids. These and other wastes have been specifically listed as solid wastes which are nonhazardous.

Organic wastes are less amenable to currently available treatment technology than are inorganic wastes. This generalization holds for a wide variety of organic compounds with a diverse array of properties which occur in common wastes streams. Wastes with greater than 10 to 20 percent organic constituents are not generally recommended for treatment by current, commercial fixation techniques as the organics interfere with the physical and chemical processes which are important in binding the waste materials together (1-4). Some processors who handle large volumes of inorganic wastes will accept relatively small volumes of selected organic wastes which are mixed to a low concentration in the inorganic waste treatment stream.

Organic wastes lend themselves to destructive treatment by processes such as incineration, UV-ozone or biological systems. Such treatments properly employed produce innocous products (mainly $CO_2$ and water) which after scrubbing can be vented directly to the atmosphere. Since the hazardous organic-waste components are destroyed, all of the problems associated with ultimate disposal such as leachate or vapor losses, land use and reclamation, and long-term manifest or record keeping are eliminated. Even for wastes containing only moderate to small amounts of organics, the organic fraction is often best first separated by solvent extraction or distillation so that it can be disposed of separately. The volume of ash and/or flue gas scrubber sludge left after destructive treatment will vary widely with the type of organic material being treated, but will almost always be a small fraction of the original organic waste.

In summary, the wastes most effectively stabilized/solidified consist mainly of inorganic materials in aqueous solution or suspension which contain appreciable amounts of toxic heavy metals and/or inorganic salts. It is also towards these waste types that most stabilization/solidification techniques are directed.

## 1.5 DELISTING TREATED HAZARDOUS WASTE PRODUCTS

Hazardous wastes which have undergone any treatment processes are still considered hazardous unless an exemption has been petitioned for, and granted, by the EPA for the specific waste in question. The process of removing a particular waste from the hazardous waste category (called "delisting") is considered by EPA as a modification of the original listing determination and is, therefore, treated as an amendment to the lists of hazardous waste.

To be successful, the petitioner must demonstrate that the waste produced by a particular process or treatment facility does not meet any of the criteria under which the waste which was listed as a hazardous waste. If the treated waste is a mixture of solid waste, and if one or more of the wastes is listed as hazardous (or is derived from one or more hazardous wastes), the demonstration of non-hazardous character may be made with respect to each constituent listed as a hazardous waste, or the waste mixture as a whole. If the waste is listed as hazardous because it exhibits one of the characteristics of hazardous wastes (ignitability, corrosivity, reactivity, or extractant procedure toxicity), then the petitioner must show that demonstration samples of the treated waste products do not exhibit that characteristic. The applicable testing procedures must be employed.

If any of the hazardous wastes present in the treated wastes are listed because they are made up of, or contained, toxic components then the petitioner must demonstrate that the treated waste no longer contains the toxic component, or if still present, that the toxic component is not capable of posing a substantial present or potential threat to human health or the environment. If the waste was listed because it contains an "acute hazardous waste," in addition to demonstrating lack of toxicity, the waste must be shown to be non-fatal to humans in low doses or, if human data is not available, to not be fatal to other mammals at doses higher than those prescribed.

Thus delisting of solidified/stabilized waste is possible upon the demonstration to EPA's satisfaction that the component or characteristic for which the waste was listed is no longer present or applicable to the treated product. This determination of the non-hazardous character of the waste product makes possible the much cheaper and less rigorous disposal of the wastes in any solid waste landfill. The use of the waste in any productive way (such as foundation, fill, or construction materials) must be preceded by the delisting of the product as a hazardous waste. It is unlikely that a whole waste-stream can be permanently delisted, or that a particular waste fixation process can be certified as producing a non-hazardous product irregardless of changes in the process parameters or in the wastes being treated.

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# SECTION 2

# WASTE STABILIZATION/SOLIDIFICATION TECHNOLOGY

## 2.1 CURRENT STABILIZATION/SOLIDIFICATION TECHNOLOGY

Several stabilization/solidification methods now available or under development have as their goal the safe ultimate disposal of hazardous waste either via a productive way or by landfilling. Ultimate disposal implies the final disposition of persistent, nondegradable, cumulative, and/or harmful waste. The four primary goals of treating hazardous waste for ultimate disposal are: (a) to improve the handling and physical characteristics of the waste, (b) to decrease the surface area across which transfer or loss of contained pollutants can occur, (c) to limit the solubility of any pollutants contained in the waste, and (d) to detoxify contained pollutants. These goals can be met in a variety of ways, but not all techniques attempt to meet all the goals. Thus individual treatment techniques may solve one particular set of problems but be completely unsatisfactory for others. Process selection becomes weighing advantages and disadvantages for the particular situation.

The following major categories of industrial waste fixation systems are discussed in this section:

a. Cement-based processes

b. Pozzolanic processes (not including cement)

c. Thermoplastic techniques (including bitumen, paraffin, and polyethylene incorporation)

d. Organic polymer techniques (including urea-formaldehyde, unsaturated polyester)

e. Surface encapsulation techniques (jacketing)

f. Self-cementing techniques (for high calcium sulfate sludges)

g. Glassification and production of synthetic minerals or ceramics

Examples of treated waste materials are shown in Figure 2-1. Since these waste treatment systems vary widely in their applicability, cost, and pretreatment requirements, many are limited as to the types of waste that can be economically processed. Selection of any particular technique for waste

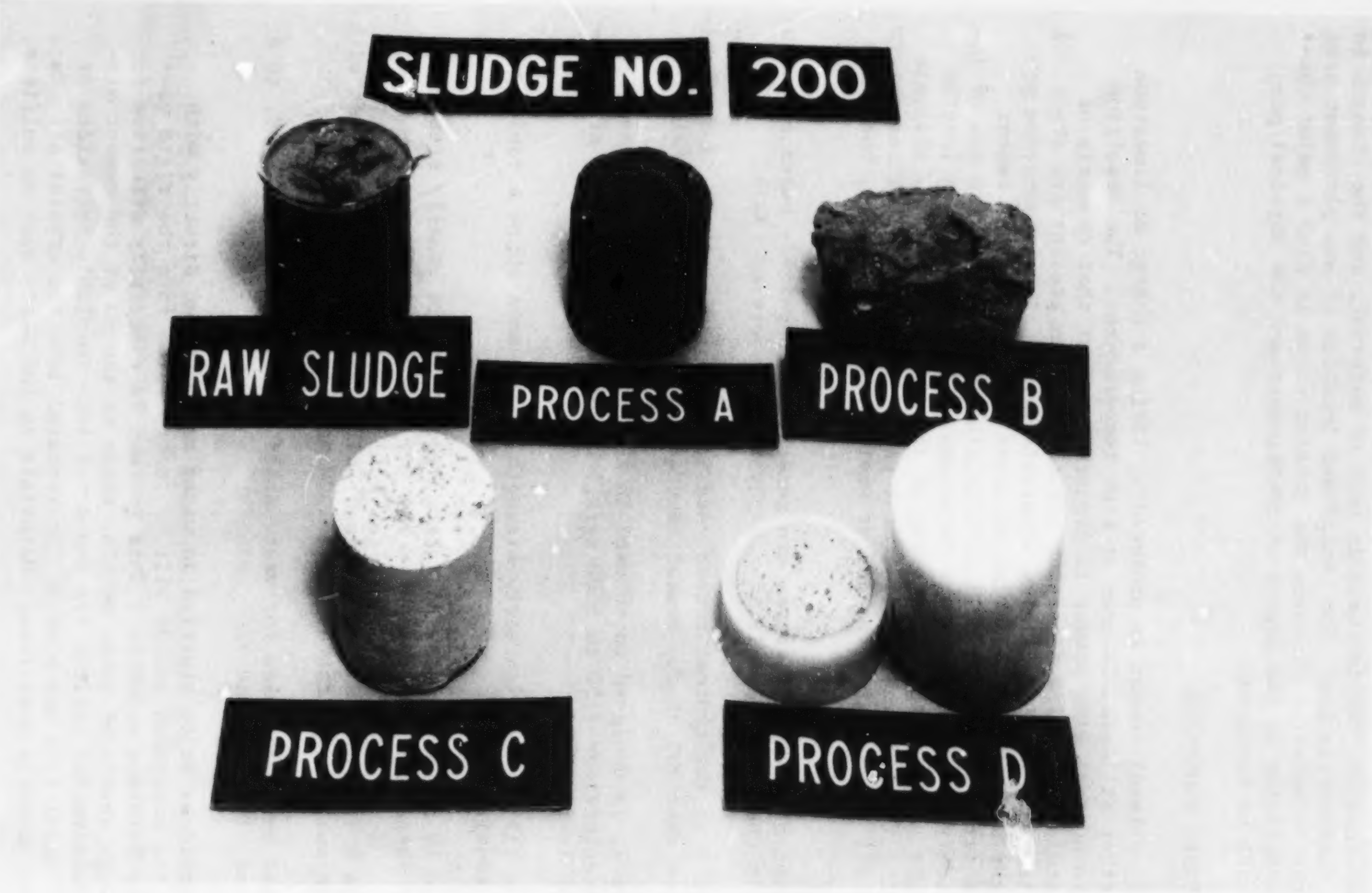
SLUDGE NO. 200
RAW SLUDGE
PROCESS A
PROCESS B
PROCESS C
PROCESS D

Figure 2-1. Examples of solidified electroplating waste. Process A is a pozzolan product, Process B is a cement based system, Process C is a urea-formaldehyde system, Process D is a plactic jacketing system.

treatment must include careful consideration of the containment required, the cost of processing, the increase in bulk of material, and the changes in the handling characteristics. The design and location of any placement area or landfill that eventually receives the treated waste is also a major consideration in deciding on the degree of containment and the physical properties that will be required.

## 2.2 CEMENT-BASED PROCESSES

Common (portland) cement is produced by firing a charge of limestone and clay or other silicate mixtures at high temperatures. The resulting clinker is ground to a fine powder to produce a cement that consists of about 50% tricalcium and 25% dicalcium silicates (also present are about 10% tricalcium aluminate and 10% calcium aluminoferrite). The cementation process is brought about by the addition of water to the anhydrous cement powder. This first produces a colloidal calcium-silicate-hydrate gel of indefinite composition and structure. Hardening of the cement is a lengthy process brought about by the interlacing of thin, densely-packed, silicate fibrils growing from the individual cement particles. This fibrillar matrix incorporates the added aggregates and/or waste into a monolithic, rock-like mass.

Five types of Portland cements are generally recognized, based on variations in their chemical composition and physical properties (3-!).

a. Type I is the typical cement used in the building trade, and constitutes over 90% of the cement manufactured in the United States.

b. Type II is designed to be used in the presence of moderate sulfate concentrations (150 to 1500 mg/kg) or where moderate heat of hydration is required.

c. Type III has an high early strength and is used where a rapid set is required.

d. Type IV develops a low heat of hydration and is usually prescribed for large-mass concrete work but has long set time.

e. Type V is a special low-alumina, sulfate-resistant cement used with high sulfate concentrations (>1500 mg/kg).

The types that have been used for waste solidification are Type I and, to a smaller extent, Types II and V.

Most hazardous waste slurried in water can be mixed directly with cement, and the suspended solids will be incorporated into the rigid matrices of the hardened concrete. This process is especially effective for waste with high levels of toxic metals, since at the pH of the cement mixture, most multivalent cations are converted into insoluble hydroxides or carbonates. Metal ions may also be incorporated into the crystal structure of the cement minerals that form. Materials in the waste such as sulfides, asbestos, latex, and solid plastic wastes may actually increase the strength and stability of the waste concrete.

Interfering Compounds--

The presence of certain inorganic compounds in the hazardous waste and the mixing water can be deleterious to the setting and curing of the waste-containing concrete (2-1). Also, impurities such as organic materials, silt, clay, or lignite may delay the setting and curing of common portland cement for as long as several days. All insoluble materials passing through a No. 200 mesh sieve ( $74 \times 10^{-6}$ m particle size) are undesirable, as they may be present as dust or may coat the larger particles and weaken the bond between the particles and the cement. Soluble salts of manganese, tin, zinc, copper, and lead may cause large variations in setting time and significant reduction in physical strength. Salts of zinc, copper, and lead are the most detrimental. Other compounds that are especially active as setting retarders in portland cement include sodium salts of arsenate, borate, phosphate, iodate, and sulfide--even at concentrations as low as a few tenths of a percent of the weight of the cement used. Products containing large amounts of sulfate (such as flue gas cleaning sludges) not only retard the setting of concrete, but by reacting to form calcium sulfoaluminate hydrate, they cause swelling and spalling in the solidified waste-containing concrete. To prevent this reaction, a special low-alumina (Type V) cement was developed for use in circumstances where high sulfate is encountered.

Additives--

A number of additives have been developed for use with cement to improve the physical characteristics and decrease the leaching losses from the resulting solidified sludge. Many of the additives used in waste treatment are proprietary and cannot be discussed here. Experimental work on the treatment of radioactive waste has shown some improvement in cement-based fixation and retention of nuclear waste with the addition of clay or vermiculite as absorbents (2-2). Soluble silicate has reportedly been used to bind contaminants in cement solidification processes, but this additive causes an increase in volume to occur during the setting of the cement-waste mixture. A recently proposed adaptation of this technique involves dissolving the metal-rich waste with fine-grained silica at low pH and then polymerizing the mixture by raising the pH to 7. The resulting contaminated gel is mixed with cement and hardens within 3 days.

Recent testing by Brookhaven National Laboratory indicates that a mixture of sodium silicate and Type II portland cement produces a rapid set with no retardation from metallic ions (2-2). The sodium silicate appears to precipitate most interfering ions in a gelatinous mass and so to remove their interferences and to speed setting. Of the wastes tested, only boric acid waste inhibited the set of the cement mixture. The development of a gel is important in the setting of the cement-waste-silicate mixtures. Excessive mixing after the gel forms seems to cause slower setting and lessen final strength of the product.

Polymer Impregnation--

The Brookhaven National Laboratory also developed a polymer impregnation process that can be used to decrease the permeability of concrete-waste mixtures (2-3). The pores of the waste-concrete are filled by soaking in styrene monomer. The soaked material is then heated to bring about polymerization. This process results in a significant increase in the strength and durability of the concrete-waste mixture.

Coatings--

Surface coating of concrete-waste composites has been examined extensively. The major problems encountered have been poor adhesion of the coating onto the waste or lack of strength in the concrete material containing the waste. Surface coating materials that have been investigated include asphalt, asphalt emulsion, and vinyl. However, no surface coating system for cement-solidified material is currently being advertised.

Advantages and Disavantages--

Advantages of the cement treatment systems are:

a. The amount of cement used can be varied to produce high bearing capacities (making the waste concrete good subgrade and subfoundation materials) and low permeability in the product.

b. Raw materials are plentiful and inexpensive.

c. The technology and management of cement mixing and handling is well known, the equipment is commonplace, and specialized labor is not required.

d. Extensive drying or dewatering of waste is not required because cement mixtures require water, and the amount of cement added can be adapted through wide ranges of water contents.

e. The system is tolerant of most chemical variations. The natural alkalinity of the cement used can neutralize acids. Cement is not affected by strong oxidizers such as nitrates or chlorates. Pretreatment is required only for materials that retard or interfere with the setting action of cement.

f. Leaching characteristics can be improved where necessary by coating the resulting product with a sealant.

Disadvantages of cement-based systems are:

a. Relatively large amounts of cement are required for most treatment processes (but this may partly be offset by the low cost of material). The weight and volume of the final product is typically about double those of other solidification processes.

b. Uncoated cement-based products may require a well-designed landfill for burial. Experience in radioactive waste disposal indicates that some wastes are leached from the solidified concrete, especially by mildly acidic leaching solutions.

c. Extensive pretreatment, more expensive cement types or additives may be necessary for waste containing large amounts of impurities such as borates and sulfates that affect the setting or curing of the waste-concrete mixture.

d. The alkalinity of cement drives off ammonium ion as ammonia gas.

e. Cement is an energy-intensive material.

## 2.3 POZZOLANIC PROCESSES (NOT CONTAINING CEMENT)

Waste fixation techniques based on lime products usually depend on the reaction of lime with a fine-grained siliceous (pozzolanic) material and water to produce a concrete-like solid (sometimes referred to as a pozzolanic concrete). The most common pozzolanic materials used in waste treatment are fly ash, ground blast-furnace salg, and cement-kiln dust. All of these materials are themselves waste products with little or no commercial value at this time. The use of these waste products to consolidate another waste is often advantageous to the processor, who can treat two waste products at the same time. For example, the production of a pozzolanic reaction with power plant fly ash permits the flue gas cleaning sludge to be combined with the normal fly ash output and lime (along with other additives) to product an easily-handled solid. Many, if not all, of the comments associated with the cement systems apply to the pozzolanic systems including advantages and disadvantages.

Advantages of lime-based treatment techniques that produce pozzolanic cement are several:

a. Product is generally a solid with improved handling and permeability characteristics.

b. The materials are often very low in cost and widely available.

c. Little specialized equipment is required for processing, as lime is a common additive in other waste streams.

d. The chemistry of lime-pozzolanic reactions are relatively well-known. Sulfate does not cause spalling or cracking.

e. Extensive dewatering is not necessary because water is required in the setting reaction.

The lime-based systems have many of the same potential disadvantages as cement-based techniques:

a. Lime and other additives add to the weight and bulk to be transported and/or landfilled.

b. Uncoated lime-treated materials may require specially designed landfills to guarantee that the material does not lose potential pollutants by leaching.

Certain treatment systems fall in the category of cement-pozzolanic processes and have been in use for some time outside the U. S. In this case both cement and lime-siliceous materials are used in combination to give the best and most economical containment for the specific waste being treated. In general, the bulk of the comments under both classifications above hold for techniques using a combination of treatment materials.

## 2.4 THERMOPLASTIC TECHNIQUES (INCLUDING BITUMEN, PARAFFIN AND POLYETHYLENE)

The use of thermoplastic solidification systems in radioactive waste disposal has led to the development of waste containment systems that can be adapted to industrial waste. In processing radioactive waste with bitumen or other thermoplastic material, the waste is dried, heated, and dispersed through a heated plastic matrix. The mixture is then cooled to solidify the mass, and it is usually buried in a secondary containment system such as a steel drum. Variations of this treatment system can use thermoplastic organic materials such as paraffin or polyethylene.

The process requires some specialized equipment to heat and mix the waste and plastic matrices, but equipment for mixing and extruding waste plastic is available. The ratio of matrix to waste is generally quite high--a 1:1 to 1:2 ratio of incorporation material to waste (on a dry-weight basis). The plastic in the dry waste must be mixed at temperatures ranging from 130° to 230°C, depending on the melting characteristics of the material and type of equipment used.

A variation of this process uses an emulsified bitumen product that is miscible with a wet sludge. In this process, the mixing can be done at any convenient temperature below the boiling point of the mixture. The overall mass must still be heated and dried before it is suitable for disposal. Ratios of emulsions to waste of 1:1 to 1:1.5 are necessary for adequate incorporation (2-2).

In many cases, the types of waste rule out the use of any organic-based treatment systems. Organic chemicals that are solvents for the matrix obviously cannot be used directly in the treatment system. Strongly oxidizing salts such as nitrates, chlorates, or perchlorates will react with the organic matrix materials and cause slow deterioration. At the elevated temperatures necessary for processing, the matrix-oxidizer mixtures are extremely flammable.

Leach or extraction testing undertaken on anhydrous salts embedded in bitumen as a matrix indicates that rehydration of the embedded compound can occur when the sample is soaked in water and can cause the asphalt or bitumen to swell and split apart, greatly increasing the surface area and rate of waste loss (2-2). Some salts (such as sodium sulfate) will naturally dehydrate at the temperatures required to make the bitumen plastic; so these easily dehydrated compounds must be avoided in thermoplastic stabilization.

The major advantages of the thermoplastic-based disposal systems are:

a. The rate of loss to contacting fluids are significantly lower than those observed with cement-based and pozzolon systems.

b. By disposing of the waste in a dry condition, the overall volume of the waste is greatly reduced.

c. Most thermoplastic matrix materials are resistant to attack by aqueous solutions, and microbial degradation is minimal.

d. Most matrices adhere well to incorporated materials.

e. Materials embedded in a thermoplastic matrix can be reclaimed if needed.

The principal disadvantages of the thermoplastic-based disposal systems are:

a. Expensive, complicated equipment requiring highly specialized labor is necessary for processing.

b. The plasticity of the matrix-waste mixtures may require that containers be provided for transportation and disposal of the materials, which greatly increases the cost.

c. The waste materials to be incorporated must be dried, which requires large amounts of energy. Incorporating wet wastes greatly increases losses through leaching.

d. These systems cannot be used with materials that decompose at high temperatures, especially citrates and certain types of plastics.

e. There is a risk of fire in working with organic materials such as bitumen at elevated temperatures.

f. During heating, some mixes can release objectionable oils and odors causing secondary air pollution.

g. The incorporation of tetraborates of iron and aluminum salts in bitumen matrices causes premature hardening, and can clog and damage the mixing equipment.

h. Strong oxidizers usually cannot be incorporated into organic materials without the occurrence of oxidizing reactions. High concentrations of strong oxidizers at elevated processing temperatures can cause fires.

i. Dehydrated salts incorporated in the thermoplastic matrix will slowly rehydrate if the mixture is soaked in water. The rehydrated salt will expand the mixture causing the waste block to fragment and increasing its surface area greatly.

## 2.5 ORGANIC POLYMER PROCESSES

Organic polymer techniques were developed as a response to the requirement for solidification of waste for transportation. The most thoroughly tested organic polymer solidification technique is the urea-formaldehyde (UF) system. The polymer is generally formed in a batch process where the wet or dry wastes are blended with a prepolymer in a waste receptacle (steel drum) or in a specially-designed mixer. When these two components are thoroughly mixed, a catalyst is added, and mixing is continued until the catalyst is thoroughly dispersed. Mixing is terminated before the polymer has formed and the resin-waste mixture is transferred to a waste container if necessary. The polymerized material does not chemically combine with the waste--it forms a spongy mass that traps the solid particles. Any liquid associated with the waste will remain after polymerization. The polymer mass must often be dried before disposal.

Several organic polymer systems are available that are not based on UF resins. Dow Industrial Division is developing a vinyl ester-styrene system (Binder 101) for use with radioactive waste (2-4). Testing of this material is currently underway in the Nuclear Regulatory Commission Research Programs.

The Polymeric Material Section at Washington State University has developed a polyester resin system that is being used in solidification of waste. This system is currently in a pilot-plant stage in the processing of hazardous wastes (2-5, 2-6, 2-7).

The major advantages of the organic polymer systems (especially the UF-resin system) are:

a. Less treatment reagent is required for solidifying the waste than in other systems. The waste-to-reagent ratio is usually about 30% greater for a UF organic polymer system than with cement.

b. The waste material treated is usually dewatered, but it is not necessarily dried as in thermoplastic processes. (The finished, solidified polymer, however, must be dried before ultimate disposal.)

c. The organic resin used is consistently less dense (specific gravity is approximately 1.3) than cement. The low density reduces the transportation cost related to the reagents and to the treated products.

d. The solidified resin is nonflammable, and high temperatures are not required in forming the resin.

The major disadvantages of the organic resin techniques, especially the UF resin systems are:

a. No chemical reactions occur in the solidification process that chemically binds the potential pollutants. The particles of waste material are trapped in an organic resin matrix, and breakdown or leaching of the matrix will release many of the waste materials.

b. Catalysts used in the UF systems are strongly acidic, and the waste-UF mixture must be maintained at pH 1.5 ± 0.5 for solidification to occur in a rapid manner. The low pH can put many waste materials into solution. If the pH is not lowered to 1.5, the polymerization is slow; solids will thus settle out, and the waste material will not be trapped effectively.

c. Uncombined or weep water is often associated with polymerized waste. This must be allowed to evaporate to produce a fully-cured polymer. This weep water may be strongly acidic and may contain high levels of pollutants. Waste-UF mixtures shrink as they age and will produce weep water during aging.

d. Some catalysts used in polymerization are highly corrosive and require special mixing equipment and container liners.

e. The reaction producing the resin may release fumes that can be harmful or disagreeable even in low concentrations.

f. Some cured resins, especially UF-based systems, are biodegradable and have a high loss of chemical oxygen demand.

g. Secondary containment in steel drums is a common practice in the use of organic resins, which increases the cost of processing and transportation.

## 2.6 SURFACE ENCAPSULATION TECHNIQUES (JACKETING)

Many waste treatment systems depend on binding particles of waste material together. To the extent to which the binder coats the waste particles, the wastes are encapsulated. However, the systems addressed under surface encapsulation are those in which a waste that has been pressed or bonded together is enclosed in a coating or jacket of inert material. A number of systems for coating solidified industrial wastes have been examined by TRW Corporation (2-3). In most cases, coated materials have suffered from lack of adhesion between coatings and bound wastes, and lack of long-term integrity in the coating materials. After investigating many alternative binding and coating systems, TRW Corporation produced detailed plans for what it considered to be the optimum encapsulation system. The TRW-developed system has been tested and published data on the processes are available (2-8).

The TRW surface encapsulation system requires that the waste material be thoroughly dried. The dried wastes are stirred into an acetone solution of modified 1,2-polybutadiene for 5 min. The mixture is allowed to set for 2 hr. The optimum amount of binder is 3% to 4% of the fixed material on a dry-weight basis. The coated material is placed in a mold, subjected to slight mechanical pressure, and heated to between 120° and 200°C (250° and 400°F) to produce fusion. The agglomerated material is a hard, tough, solid block. A polyethylene jacket 3.5 mm (1/4 in.) thick is fused over the solid block and adheres to the polybutadiene binder. In a 360- to 450-kg (800- to 1000-lb) block, the polyethylene would amount to 4% of the fused waste on a weight basis (see Fig. 2-2).

The major advantages of an encapsulation process are:

a. The waste material never comes into contact with water, therefore, soluble materials such as sodium chloride can be successfully surface encapsulated.

b. The impervious jacket eliminates all leaching into contacting waters as long as the jacket remains intact.

The major disadvantages of encapsulation are:

a. The resins required for encapsulating are expensive.

b. The process requires large expenditures of energy in drying, fusing the binder, and forming the jacket.

c. Polyethylene is combustible, with a flash point of 350°C, making fires a potential hazard.

d. The system requires extensive capital investment and equipment.

e. Skilled labor is required to operate the molding and fusing equipment.

## 2.7 SELF-CEMENTING PROCESSES

Some industrial wastes such as flue-gas cleaning or desulfurization sludges contain large amounts of calcium sulfate and calcium sulfite. A technology has been developed to treat these types of wastes so that they become self-cementing (2-9). Usually a small portion (8% to 10% by weight) of the dewatered waste sulfate/sulfite sludge is calcined under carefully controlled conditions to produce a partially dehydrated cementitious calcium sulfate or sulfite. This calcined waste is then reintroduced into the bulk of the waste sludge along with other proprietary additives. Fly ash is often added to adjust the moisture content. The finished product is a hard, plaster-like material with good handling characteristics and low permeability. The major advantages of self-cementing systems are:

a. The material produced is stable, nonflammable, and nonbiodegradable.

b. There are reports of effective heavy metal retention, which is perhaps related to chemical bonding of potential pollutants.

c. No major additives have to be manufactured and shipped to the processing site.

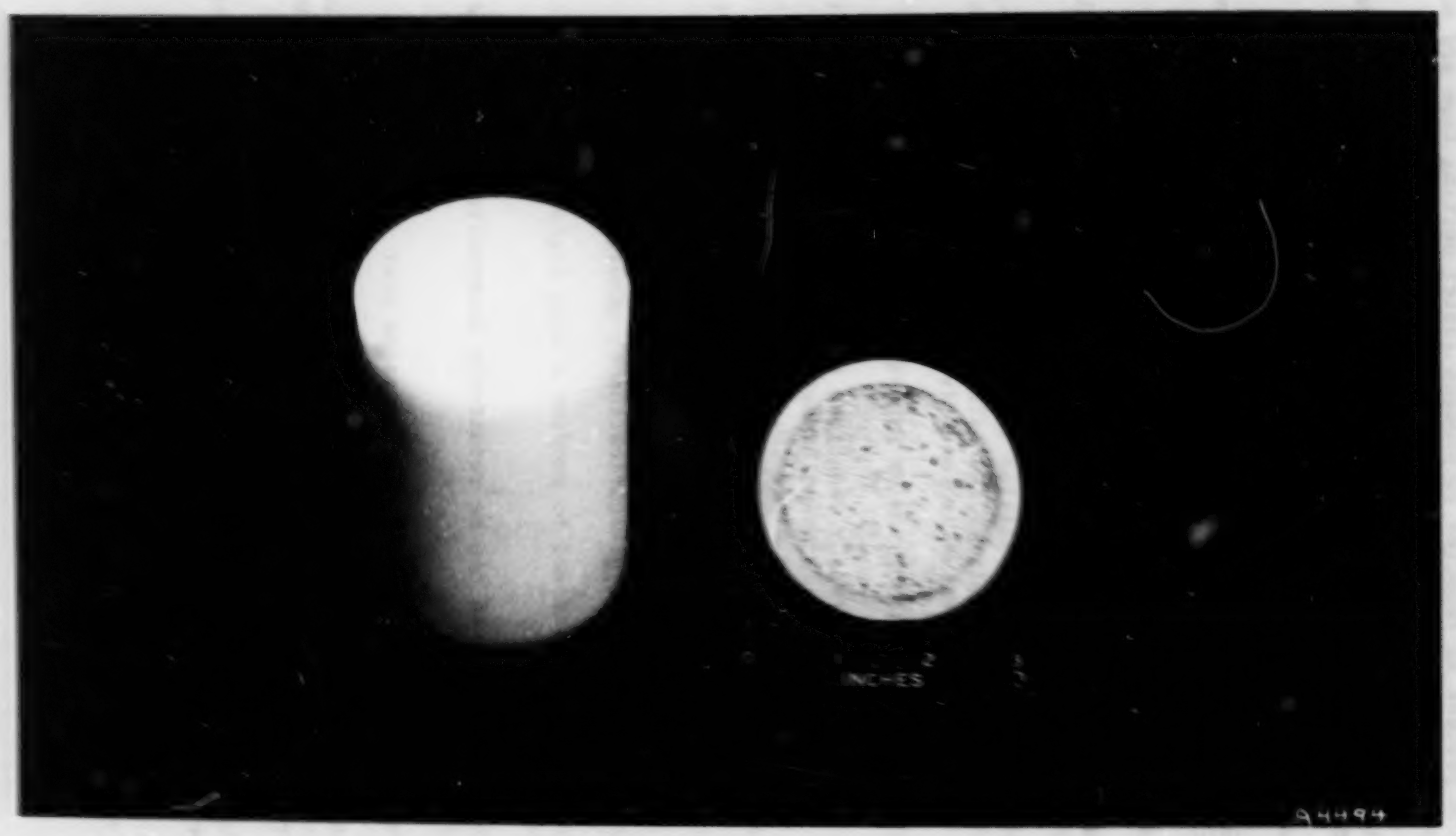
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Figure 2-2. Close-up of plastic-jacketed electroplating waste.

d. The process is reported to produce faster setting time and more rapid curing than comparable lime-based systems.

e. These systems do not require completely dry waste. The hydration reaction uses up water.

The major disadvantages of self-cementing systems are:

a. Self-cemented sludges have much the same leaching characteristics as cement and lime-based systems.

b. Only high calcium sulfate or sulfite sludges can be used.

c. Additional energy is required to produce the calcined cementitious material.

d. The process requires skilled labor and expensive machinery in calcining wastes and mixing the calcined wastes back to the bulk of the waste with proprietary additives.

## 2.8 GLASSIFICATION AND PRODUCTION OF SYNTHETIC MINERALS OR CERAMICS

Where material is extremely dangerous or radioactive, it is possible to combine the waste with silica and either fuse the mixture in glass or to form a synthetic silicate mineral (2-10, 2-11). Glasses or crystalline silicates are only very slowly leached by naturally occurring waters, so these waste products are generally considered to be safe materials for disposal without secondary containment. No work using glassification of industrial wastes are now going on.

The major advantages of glassification or mineral synthesis are:

a. The process is assumed to produce a high degree of containment of wastes.

b. The additives used can be relatively inexpensive (syenite and lime).

The major disadvantages of these processes are:

a. Some constituents (especially metals) may be vaporized and lost before they can bind with the molten silica if high-temperature processes are used.

b. The process is energy-intensive. The waste-silicate charge must be heated (often up to 1350°C) for melting and fusion.

c. Sepcialized equipment and trained personnel are required for this type of operation.

## 2.9 SUMMARY

A wide variety of possible techniques exist for waste treatment. Obviously, no system is applicable to every waste in all situations. The amount and character of the material to be stabilized, the economics involved and the properties of the disposal site (see Section 7) are all important factors in deciding which treatment procedures are best for any given situation. By careful evaluation of economics, the hazardous nature of the material, and the containment provided by geologic and hydrologic situations at nearby landfills, it should be possible to establish a minimum cost for responsible disposal of a particular waste. A list of companies marketing stabilization/solidification technology in the United States is given in Appendix B.

The cost for waste treatment processes depends on the volume of the waste to be fixed. Therefore, it may become cost-advantageous to concentrate hazardous wastes into a minimum volume to reduce handling and additive requirements. When hazardous wastes are concentrated, the precautions involved in handling and transportation are necessarily increased, so onsite stabilization or solidification is desirable. In fact, stabilization/solidification may become a unit operation to complete a waste treatment system. The waste treatment operations could be tailored to produce the hazardous residue in a minimum volume with a pH and chemical composition compatible with the treatment system that is required to insure safe containment under specific landfill conditions.

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## SECTION 3

## PROPERTIES OF STABILIZED/SOLIDIFIED WASTES

Selection of the best treatment system requires detailed knowledge of the constituents and characteristics of the waste to be treated, the amount of waste to be handled, and the location and environment of the waste disposal site. This section deals with the characteristics that an ideal treatment system and its product would be expected to have and the major considerations that are involved in the selection of the best treatment system for a specific waste stream.

### 3.1 CHARACTERIZING OF WASTES TO BE TREATED

The first step in selection of the best system involves a detailed knowledge of the wastes to be treated. A complete inventory of all constituents in the waste streams should be made. The source and amount of each waste type (including the process or operation that produces it, how it is transported, stored, and treated, and its production rate and production schedule) should be determined. This information is necessary for selection processes and will be required for disposal planning.

A complete knowledge of all components of all waste streams at a particular site is of great importance. Much information can be gained from the knowledge of the process or operation by which the waste is produced. This detailed information should include types of materials and concentrations, organic constituents, solvents, etc. Where organics are present, it is essential to know details about chemical stability, flash points, and heating value. The inorganic components and their relative concentrations must be determined. Toxic heavy metals, even in small concentrations, are a major concern. The pH, buffering capacity, and water content of the waste are of critical importance in many solid waste treatment systems.

### 3.2 REQUIREMENTS FOR IDEAL WASTE STABILIZATION/SOLIDIFICATION

The ideal fixation process renders the noxious constituents chemically nonreactive and/or immobile so that no secondary containment is necessary for safe disposal. For example, incorporation into a stable crystal lattice effectively isolates noxious materials from any environmental interactions, and maintaining the pH in the range of 9 to 11 immobilizes most multivalent cations as insoluble hydroxides and other compounds. Sludges with high concentrations of particular cations can be treated with additives chosen specifically to immobilize these contaminants. Anions, although typically much less toxic, are much more difficult to bind into an unleachable product. Chlorides and sulfates, the most common anionic sludge components, produce only a few insoluble salts. To contain anions such as these the waste must be physically isolated from any leaching medium by secondary containment or special landfill covers.

To be completely effective, the waste treatment must produce a final mixture whose physical properties are such that its disposal does not permanently render the land unsuitable for alternative uses such as building sites or agriculture. However, the production of treated wastes with "soil-like" character that might be suitable for agricultural use seems unlikely in cases where the major contaminants are toxic metals, certain organics, and/or high levels of salt. The long-term action of organic acids normally produced by the biological activity in agricultural soils would be expected to mobilize even the most tightly bound contaminant eventually. Such mobilized constituents would then be taken into the food chain or washed into the groundwater. The most secure final form of treated waste appears to be monolithic mass that has good dimensional stability, freeze-thaw resistance, low permeability, a high bearing capacity, and resistance to attack by biological agents. An end product such as this could be used as a foundation for buildings or roads, or simply buried and covered over in a landfill.

The ideal treatment process does not require extensive heat treatment or large amounts of energy-intensive reactants. Also, the waste material should be reclaimable by some reasonable technique, since some of the sludge contaminants (e.g., manganese and chromium) are predicted to be in critical supply in the future.

These are rather stringent requirements for any waste treatment process. A great deal of study by private industry and government is going into the development of better treatment procedures. However, with current technology and with complete knowledge of the waste to be treated and the treatment processes available, the production of finished products that will approximate the ideal stabilized material is possible.

## 3.3 COMPATIBILITY OF WASTES AND TREATMENT ADDITIVES

As in any hazardous waste handling operation, care must be taken during stabilization/solidification to avoid mixing together materials that can react with one another in a detrimental way. In waste treatment, this requirement of nonreactivity must also apply to the reagents or materials used in treatment. Potential detrimental consequences of mixing wastes include:

a. Heat generation.

b. Release of toxic materials or flammable gases.

c. Fi[illegible] or explosion.

Table 3-1 summarizes some typical reactions that could occur during hazardous waste treatment and handling.

## TABLE 3-1. REACTIONS OCCURRING BETWEEN INCOMPATIBLE WASTES*

| Waste | Incompatible waste | Potential consequences |
|---|---|---|
| Bases:<br>Acetylene sludge<br>Alkaline caustic liquids<br>Alkaline cleaner<br>Alkaline corrosive liquids<br>Alkaline corrosive battery fluid<br>Caustic wastewater<br>Lime sludge and other corrosive alkalies<br>Lime wastewater<br>Lime and water<br>Spent caustic | Acids:<br>Acid sludge<br>Acid and water<br>Battery acid<br>Chemical Cleaners<br>Electrolyte, acid<br>Etching acid liquid or solvent<br>Liquid cleaning compounds<br>Pickling liquor and other corrosive acids<br>Spent acid<br>Spent mixed acid<br>Spent sulfuric acid | Heat generation, violent reaction |
| Toxic materials:<br>Asbestos waste, and other toxic wastes<br>Beryllium wastes<br>Unrinsed pesticide containers<br>Waste pesticides | Flammable materials:<br>Cleaning solvents<br>Data processing liquid<br>Obsolete explosives<br>Petroleum waste<br>Refinery waste<br>Off-spec explosives<br>Solvents<br>Waste oil and other flammable and explosive wastes | Release of toxic substance in case of fire or explosion |
| Reactive metals<br>Aluminum<br>Beryllium<br>Calcium<br>Lithium<br>Magnesium<br>Potassium<br>Sodium<br>Zinc powder and other reactive metals and metal hydrides | Strong acids or bases:<br>Acidic or basic wastes listed above | Fire or explosion; generation of flammable hydrogen gas |

(Continued)

* Modified from: "Law, Regulations and Guidelines for Handling of Hazardous Waste." California Department of Health, February 1975; and Federal Register, Vol 45, No. 98--Appendix V, page 33258.

## TABLE 3-1 (Concluded)

| Waste | Incompatible waste | Potential consequences |
|---|---|---|
| Aqueous materials:<br>Alcohols<br>Water | Strongly reactive anhydrous materials:<br>Calcium<br>Lithium<br>Metal hydrides<br>Potassium<br>SO$_2$,Cl$_3$, SOCl$_3$, PCl$_3$, CH$_3$SiCl$_3$, and other water-reactive wastes | Fire, explosion, or heat generation of flammable or toxic gases |
| Reactive organics:<br>Alcohols<br>Aldehydes<br>Halogenated hydrocarbons<br>Nitrated hydrocarbons and other reactive organic compounds and solvents<br>Unsaturated hydrocarbons | Strong acids or bases or reactive metals, as listed above | Fire, explosion, or violent |
| Cyanides and sulfides:<br>Spent cyanide and sulfide solutions | Acids, as listed above | Generation of toxic hydrogen cyanide or hydrogen sulfide gas |
| Strong oxidizers:<br>Chlorates and other strong oxidizers<br>Chlorine<br>Chlorites<br>Chromic acid<br>Hypochlorites<br>Nitrates<br>Nitric acid, fuming<br>Perchlorates<br>Permanganates<br>Peroxides | Reduced materials:<br>Flammable materials<br>Reactive metals<br>Reactive organics<br>Organic acids | Fire, explosion, or violent reaction |

Many treatment systems require the mixing of reactive waste and/or reagents of many kinds to produce a more stable or nonreactive product. This process requires great expertise and knowledge of the precise nature and composition of the waste and of the waste reagents. Such mixing is typically carried out in treatment systems which accept diverse types of waste from diverse sources.

In addition to waste incompatibility problems, it is also necessary to note incompatibility of waste and stabilization/solidification materials over both long and short time periods. Though many reactions between waste materials and treatment reagents occur very slowly, the result may be accelerated deterioration of the treated waste and loss of containment properties. Table 3-2 summarizes major incompatibility problems that can be encountered with various waste solidification/stabilization techniques. Most of the difficulties are similar to those found in any hazardous waste handling operation. For example, without great care and knowledge, oxidizers and easily oxidized materials should not be mixed; strong acids, and strong bases should not be combined; cyanides and sulfides should not be acidified; and organic solvents must be isolated from soluble materials they attack or dissolve.

Some solidifying reagents may never set or harden if the wastes contain inhibiting materials. Silicate polymer reactions can be slowed by organics or high concentrations of certain metals. Organic polymers can be broken down by solvents, strong oxidizers, or strong acids (Table 3-3). Organic polymers are also degraded by ultraviolet radiation (exposure to sunlight).

Care must be taken in all systems requiring the mixing of hazardous wastes with other waste materials or with reagents required for solidification or stabilization. In general, the silicate-based (cement or pozzolan) containment systems are most tolerant to a wide variety of wastes, both inorganic and organic.

## 3.4 TESTING THE PHYSICAL PROPERTIES OF STABILIZED WASTES

The physical properties of the waste are modified by the stabilization/solidification process. The end product of many treatment processes is a solid block resembling low-strength concrete, which can be subjected to standard tests of physical properties so that its durability under field conditions can be predicted (3-1). Some processes produce a friable or soil-like product that must be subjected to tests more typically used for soil-cement (3-2). Prediction of chemical containment characteristics of these stabilized wastes from physical properties is much more difficult than prediction of long-term physical characteristics.

The primary aims of physical testing of treated and untreated wastes are to (1) determine particle size distribution, porosity, permeability and wet and dry densities, (2) evaluate their bulk properties, (3) predict the reaction of a material to applied stress in embankments, landfills, etc., and (4) evaluate durability. A variety of physical properties tests are

## TABLE 3-2. COMPATIBILITY OF SELECTED WASTE CATEGORIES WITH DIFFERENT WASTE SOLIDIFICATION/STABILIZATION TECHNIQUES

| | Treatment Type | | | | | | |
|---|---|---|---|---|---|---|---|
| Waste component | Cement based | Lime based | Thermoplastic solidification | Organic polymer (UF)* | Surface encapsulation | Self-cementing techniques | Glassification and synthetic mineral formation |
| Organics: | | | | | | | |
| 1. Organic solvents and oils | Many impede setting, may escape as vapor | Many impede setting, may escape as vapor | Organics may vaporize on heating | May retard set of polymers | Must first be absorbed on solid matrix | Fire danger on heating | Wastes decompose at high temperatures |
| 2. Solid organics (e.g., plastics, resins, tars) | Good—often increases durability | Good—often increases durability | Possible use as binding agent | May retard set of polymers | Compatible—many encapsulation materials are plastic | Fire danger on heating | Wastes decompose at high temperatures |
| Inorganics: | | | | | | | |
| 1. Acid wastes | Cement will neutralize acids | Compatible | Can be neutralized before incorporation | Compatible | Can be neutralized before incorporation | May be neutralized to form sulfate salts | Can be neutralized and incorporated |
| 2. Oxidizers | Compatible | Compatible | May cause matrix break down, fire | May cause matrix break down | May cause deterioration of encapsulating materials | Compatible if sulfates are present | High temperatures may cause undeable reactions |
| 3. Sulfates | May retard setting and cause spalling unless special cement is used | Compatible | May dehydrate and rehydrate causing splitting | Compatible | Compatible | Compatible | Compatible in many cases |
| 4. Halides | Easily leached from cement, may retard setting | May retard set, most are easily leached | May dehydrate | Compatible | Compatible | Compatible if sulfates are also present | Compatible in many cases |
| 5. Heavy metals | Compatible | Compatible | Compatible | Acid pH solubilizes metal hydroxides | Compatible | Compatible if sulfates are present | Compatible in many cases |
| 6. Radioactive materials | Compatible | Compatible | Compatible | Compatible | Compatible | Compatible if sulfates are present | Compatible |

* Urea-Formaldehyde resin.

## TABLE 3-3. LONG-TERM CHEMICAL RESISTANCE OF ORGANIC POLYMERS (RESINS) USED IN SOLIDIFICATION*

| Chemical | Resistance of resins | | |
|---|---|---|---|
| | Conventional polyethylene | Linear (high density) polyethylene | Polyvinyl chloride |
| Acetic acid 50% | Excellent | Excellent | Moderate |
| Benzene | Poor | Moderate | Not resistant |
| Butadiene | Not resistant | Not resistant | Not resistant |
| Carbon tetrachloride | Poor | Moderate | Moderate |
| Chloroform | Poor | Moderate | Not resistant |
| Chromic Acid | Excellent | Excellent | Excellent |
| Cresol | Poor | Poor | Poor |
| Dichlorobenzene | Poor | Poor | Not resistant |
| Diethyl ether | Not resistant | Not resistant | Not resistant |
| Gasoline | Poor | Moderate | Poor |
| Metallic salt sol. | Excellent | Excellent | Excellent |
| Sulfuric acid (conc.) | Moderate | Moderate | Not resistant |
| Trichloroethane | Not resistant | Not resistant | Not resistant |

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* Adapted from information given by Nalge Chemical Company.

TABLE 3-4. STANDARD TESTS OF PHYSICAL PROPERTIES

| Test | Source |
|---|---|
| Bulk and dry unit weight | Appendix II of EM 1110-2-1906* |
| Unconfined compressive strength | Appendix XI of EM 1110-2-1906 and ASTM Method D2166-66** |
| Permeability | Appendix VII of EM 1110-2-1906 |
| Wet/dry durability | ASTM Method D559-57 |
| Freeze/thaw durability | ASTM Method D560-57 |

* See Reference 3-3.
** See Reference 3-4.

applicable to treated and untreated wastes. Five standardized tests that have been used in the past and for which some data are available are discussed briefly. A complete description of these testing procedures can be found in the sources listed in Table 3-4.

### 3.4.1 Bulk and Dry Unit Weight

The bulk unit weight is the weight (solids plus water) per unit of total volume of material mass, irrespective of the water content (see Table 3-4). The dry unit weight is the ratio of the oven-dried weight to the total volume. The volume of the sample tested is usually computed from measurements of a regularly shaped mass produced by molding or trimming. The drying temperature used to obtain the dry weight of the material should be specified. Unit weights provide information for weight-volume relationships and are used to compute earth pressure or over-dirt pressure in construction. They are a measure of density and, indirectly, of void volume.

### 3.4.2 Unconfined Compressive Strength

The unconfined compressive strength is defined as the maximum unit axial compressive stress at failure or at 15% strain, whichever occurs first (see Table 3-4). The unconfined compressive strength test is applicable only to cohesive or cemented material. To determine compressive strength, a cylindrical specimen is prepared and loaded axially. The results are usually presented as a graph of compressive stress sustained by the sample versus strain. The shear strength of a cohesive material is obtained by multiplying the unconfined compressive strength by 0.5. Shear strength is an important factor in determining ultimate bearing capacity of the treated waste, stability of the embankments formed from solidified wastes, and pressure against retaining walls surrounding waste materials. Figure 3-1 shows testing of jacketed materials.

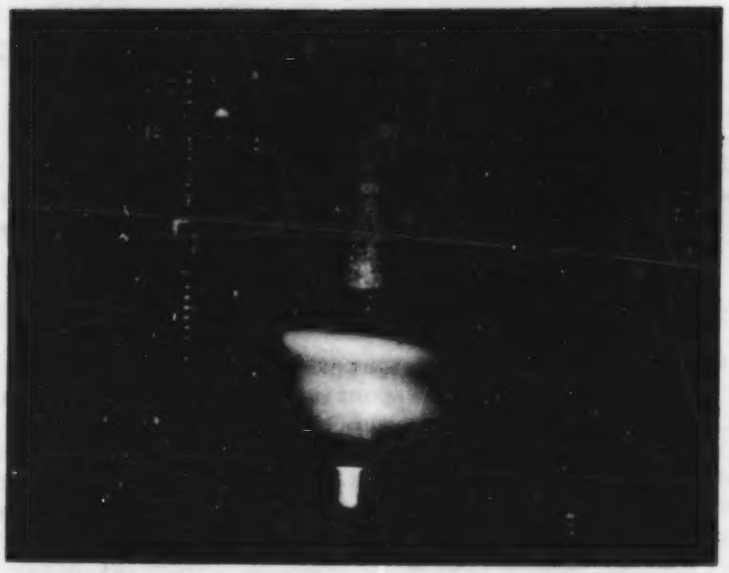

**Figure 3-1. Compression testing of plastic-jacketed wastes.**

### 3.4.3 Permeability

Permeability can be defined as the ability of a material to conduct or discharge water when placed in a hydraulic gradient (3-3). The permeability of a material depends on various parameters, including density, degree of saturation, and particle size distribution. Previous work has indicated that two types of tests are needed for determining permeability of treated and untreated sludges (3-2). A falling head permeability test can be used on raw sludges, and fixed sludges can be tested using a modified constant head test in a triaxial compression chamber with back pressure used to ensure complete saturation. A complete description of the two tests can be found in the USAE Soil Testing Manual (3-3). The permeability of a material indicates the ability of the material to permit or prohibit the passage of water. Permeability is an important factor in waste disposal because it influences the rate at which contaminants in the waste may be released to the environment.

### 3.4.4 Wet/Dry Durability

The wet/dry durability test is used to evaluate the resistance of soil-cement mixtures to the natural weathering stress of wetting and drying. In the test procedure (see Table 3-4), cured specimens are subjected to 12 test cycles, each consisting of 5 hr of submergence in water and 42 hr of low-temperature oven drying. Each cycle is followed by two firm strokes on all surface areas with a wire scratch brush. Test results are generally expressed as weight loss after 12 wet-dry cycles or the number of cycles that cause sample disintegration, whichever occurs first. Specimens that fail this type of test cannot be expected to have good long-term containment properties for those processes that depend upon isolating the waste. Figure 3-2 shows typical solidification test specimens after 4 wet-dry test cycles.

### 3.4.5 Freeze/Thaw Durability

The freeze/thaw durability test is used to evaluate the resistance of soil-cement mixtures to the natural weathering stress of freezing and thawing. In the test (see Table 3-4), cured specimens are subjected to 12 test cycles, each consisting of freezing for 24 hr, thawing for 23 hr, and two firm strokes with a wire scratch brush on all surface areas. Performance is evaluated by determining the weight loss after 12 cycles or the number of cycles that cause disintegration, whichever occurs first. Specimens that lack freeze/thaw durability must be protected from frost if containment is to succeed for those processes that depend upon isolating the waste or lessening its surface area.

### 3.4.6 Summary

Some typical results of physical testing of stabilized and untreated industrial waste are listed in Table 3-5. The data show that stabilization processes generally increase density and strength, and decrease permeability. Note that many of the treated sampes lack durability. The most striking feature of these results is the treatment processes do not produce

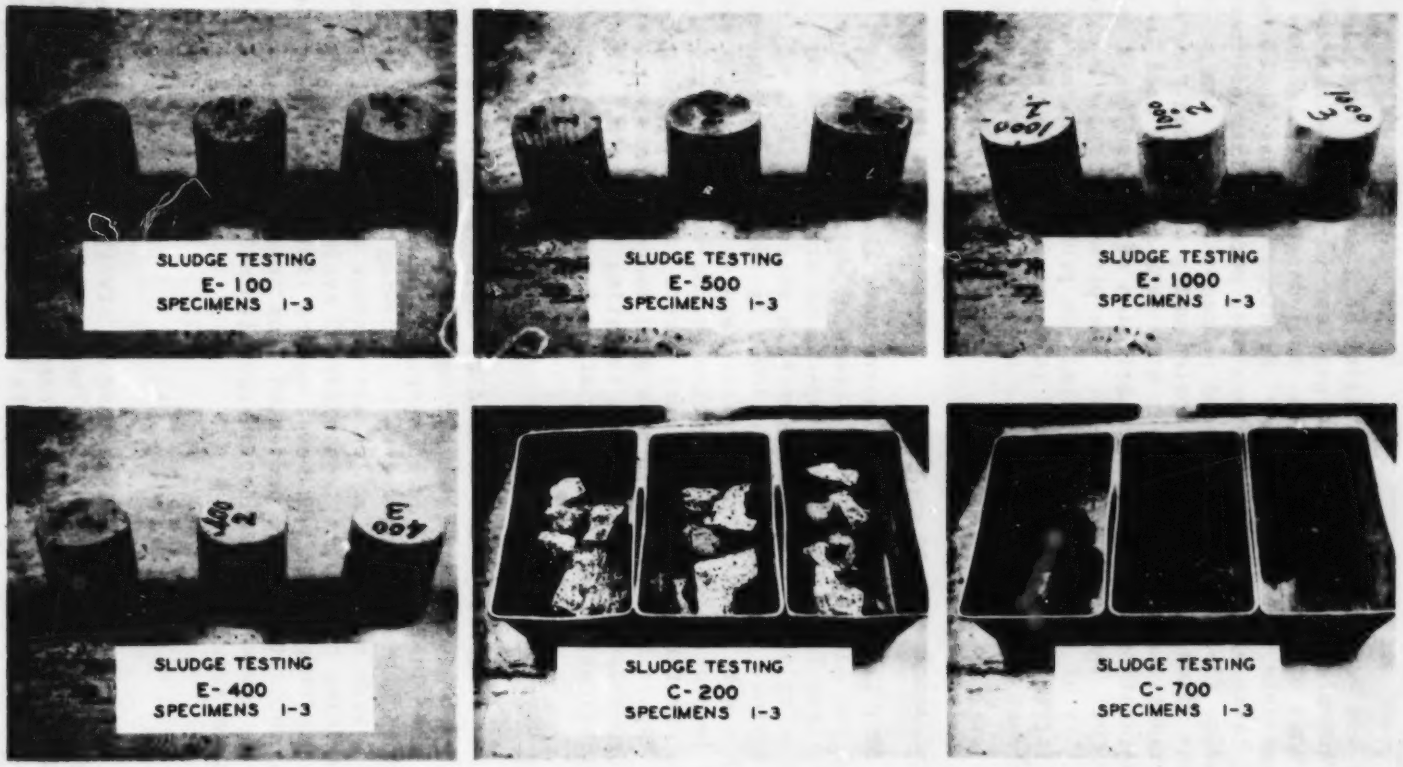
SLUDGE TESTING
E- 100
SPECIMENS 1-3
SLUDGE TESTING
E- 500
SPECIMENS 1-3
1000 1
1000 2
1000 3
SLUDGE TESTING
E- 1000
SPECIMENS 1-3
400 2
400 3
SLUDGE TESTING
E- 400
SPECIMENS 1-3
SLUDGE TESTING
C- 200
SPECIMENS 1-3
SLUDGE TESTING
C- 700
SPECIMENS 1-3

Figure 3-2. Typical solidified waste test specimens after 4 wet-dry test cycles. (Samples solidified with cement and fly-ash; #100, 400 and 1000 are flue gas cleaning sludges; #200 is an electroplating waste sludge; and #700 is an inorganic pigment production sludge.)

## TABLE 3-5. TYPICAL RESULTS FROM PHYSICAL TESTING OF STABILIZED AND UNTREATED INDUSTRIAL WASTES

| Type of waste and treatment | Unit weight: Bulk ($lb/ft^3$) | Unit weight: Dry ($lb/ft^3$) | Unconfined compressive strength ($lb/in.^2$) | Permeability (cm/sec) | Durability (test cycles to failure): Wet/dry | Durability (test cycles to failure): Freeze/thaw |
|---|---|---|---|---|---|---|
| **Nickel - Cadmium battery waste:** | | | | | | |
| Untreated | —* | 43.9 | — | $5.7 \times 10^{-6}$ | — | — |
| Lime-based pozzolan product | 104.0 | 86.2 | 169.0 | $1.9 \times 10^{-6}$ | 9 | — |
| Patented additives, soil-like material | 93.2 | 47.3 | 7.96 | $1.9 \times 10^{-4}$ | 1 | 1 |
| **Chlorine production waste:** | | | | | | |
| Untreated | — | 64.0 | — | $1.0 \times 10^{-4}$ | — | — |
| Lime-based pozzolan product | 103.0 | 88.6 | 133.0 | $8.5 \times 10^{-7}$ | — | — |
| Patented additives, soil-like material | 106.0 | 81.3 | 21.6 | $3.6 \times 10^{-5}$ | 2 | 1 |
| **Calcium fluoride waste:** | | | | | | |
| Untreated | — | 46.8 | — | $3.5 \times 10^{-5}$ | — | — |
| Lime-based pozzolan product | 85.9 | 66.6 | 26.2 | $3.8 \times 10^{-5}$ | 1 | 1 |
| Patented additives, soil-like material | 86.2 | 52.8 | 25.6 | $8.7 \times 10^{-6}$ | 1 | 2 |
| **Electroplating waste:** | | | | | | |
| Untreated | — | 28.1 | — | $3.1 \times 10^{-5}$ | — | — |
| Lime-based pozzolan product | 100.0 | 77.4 | 77.3 | $4.0 \times 10^{-7}$ | 5 | — |
| Patented additives, soil-like material | 87.1 | 47.4 | 32.4 | $1.1 \times 10^{-5}$ | 2 | — |
| Organic resin, rubber-like material | 75.4 | 52.7 | 747.0 | $1.1 \times 10^{-4}$✱ | 1 | 12 |
| Plastic encapsulation | 73.6 | 73.6 | 1540.0 | Impervious | NF(0.00)+ | NF(0.00)+ |
| **Flue gas cleaning waste:** | | | | | | |
| Untreated | — | 58.8 | — | $3.6 \times 10^{-5}$ | — | — |
| Lime-based pozzolan product | 100.0 | 80.9 | 100.0 | $2.0 \times 10^{-6}$ | 3 | 2 |
| Patented additives, soil-like material | 77.0 | 43.4 | 23.7 | $1.6 \times 10^{-4}$ | 1 | 1 |
| Cement-based, concrete-like product | 101.0 | 94.9 | 2570.0 | $7.9 \times 10^{-4}$✱ | NF(15.80)+ | 10 |

* -- Not tested.

✱ Value questionable because flow restriction caused by sample support may have influenced flow through sample.

+ NF indicates no failure in 12 cycles; figures in parentheses is the percent weight lost after 12 cycles.

products with similar physical properties. The lime-based pozzolan products are similar to low-strength concrete with high bulk and dry unit weights, relatively high compressive strengths, and low permeability. The cement-based, concrete-like product also has these same properties. The soil-like product on the other hand had little increased strength and had increased permeability. Strength and impermeability would be of value if isolation of the waste constituents in a strong, monolithic block of material was the intent of the treatment process. Dense, impervious products would be expected to lose little pollutant to the environment because of the decreased surface area of waste that is exposed to the leaching medium. The solidified blocks must be nearly impermeable to produce effective containment, because even small volumes of water moving through the waste will carry off appreciable amounts of contaminants. A large difference between bulk unit weight and dry unit weight is indicative of a large amount of pore space (void space), which allows for a high permeability and/or relatively rapid diffusion of materials from within the solidified waste. Plastic encapsulation (see electroplating waste in Table 3-5) yields the optimum result of producing an impermeable material. The plastic coating over the waste completely blocks water passage in or out of the waste so that the bulk and dry unit weights are identical, and the permeability is unmeasurably low (i.e., the block is impervious). Very little diffusion of material or flow in or out of this product is possible as long as the jacket remains intact.

The process using patented additives to produce a soil-like material attempts to stabilize the waste constituents using a different procedure. Basically the process adjusts the pH to a preselected range and then adds an ingredient (sodium silicate) that tightly binds the inorganic constituents of the waste so that they will be held in the treated waste matrix. The end result is a soil-like waste mixture that has a high differential between bulk and dry unit weights (large amount of pore space), low strength, and relatively high permeability. This system depends on precipitation and adsorption phenomena to produce containment.

Preliminary results indicate that either treatment system, physical isolation or chemical immobilization, can be effective for specific waste contaminants. Physical properties alone are not effective in predicting the ability of any treatment process to contain a particular waste type. Detailed knowledge of the method of containment of a particular treatment process and of the waste to be treated is necessary before the physical properties have any predictive value.

### 3.4.7 Other Tests of Physical Properties

Other physical tests may be appropriate for determining the suitability of treatment processes for wastes with different or unusual properties or for specialized applications of the final treated waste product.

Soil Tests--

Additional soil analyses that might prove useful with treated wastes under special circumstances include tests for compaction, Atterberg limit, triaxial compression, and bearing capacity. Compaction tests are used to determine the maximum unit weight or minimum void ratio that can be obtained for a soil-like material. The density of this material has a maximum at the optimum water content. A compaction test is generally conducted on soils or treated wastes to determine suitability for use in a landfill where structures are to be placed on the site.

Atterberg limit tests are used to determine the water content at the boundaries between liquid and plastic states. The tests are applicable only to fine-grained cohesive materials. The water contents are used to estimate properties such as compressibility, strength and swelling characteristics, which provide an indication of how the material will react when stressed.

Triaxial compression tests are used to determine the shear strength of soil-like materials under controlled drainage conditions. The shear strength provides an indication of the bearing capacity of the material and the stability of embankments constructed of the material. Bearing tests are commonly used to evaluate subgrades for pavements. These tests provide structural settling data with regard to applied load for the material being tested. Since some waste samples that appear stable or solid may liquefy if vibrated, strength determinations should include a vibrated series of specimens.

One area of soils testing that has been generally ignored but that has application for landfilling of treated sludge or waste is trafficability testing. Disposal of stabilized waste in any large quantities requires the use of tracked and wheeled vehicles to move and place the material. It is important to know what type of vehicle can be used on the material and what, if any, curing time is required before a vehicle can cross it. This information can be obtained by performing cone penetration tests along with other soil tests already discussed. Most earthmoving equipment companies can provide the information needed on their particular equipment to complete trafficability evaluations.

### Concrete Tests--

Of the additional concrete tests that are applicable to soil-cement mixtures, one test in particular that might prove useful in evaluating stabilized waste for commercial use is a strength versus curing time test. In this test, a determination similar to the unconfined compressive strength test is used to determine the compressive strength of the curing cement-waste mixture. Strength tests are generally conducted each day until maximum strength is reached. Strength versus curing time tests are useful for determining the necessary curing time needed for safe application of a load to a material after placement.

The problem noted with regard to sulfate reaction in stabilized sludges indicates that a swelling test of the type used with concrete might also be appropriate. Standard swelling tests use a sulfate solution (3-5). A simple adaptation of this test can be made by substituting distilled water for the sulfate solution used with concrete samples. Significant changes and dimensions and/or loss of strength and spalling indicates a failure.

The additional testing procedures described above are useful in evaluating stabilized sludges that are to be used in special applications. The additional cost of these tests cannot be justified for routine landfilling operations.

## 3.5 CHEMICAL LEACH TESTING OF STABILIZED WASTES

### 3.5.1 General

Chemical leach testing of wastes is a technique that is used to examine or predict the chemical stability of treated wastes when they are in contact with aqueous solutions that might be encountered in a landfill. The procedures demonstrate the degree of immobilization of contaminants produced by the treatment process. A great number of techniques for leach testing are available (3-6). Unfortunately, no single leach testing system can duplicate the variable conditions that may be encountered by landfilled treated wastes.

Most test procedures are conducted at temperatures (20° to 25°C) and pressures normally occurring in the laboratory. The major variables encountered in comparing different leaching procedures are:

1. Nature of the leaching solution.
2. Waste-to-leaching solution ratios.
3. Number of elutions of leaching solution used.
4. The time of contact of waste and leaching solution.
5. Surface area of waste.
6. Agitation technique employed.

There is no uniform opinion as to how each of these variables should be treated in a testing procedure (3-7).

Nature of the Leaching Solution--

Ideally, the leaching solution employed in any testing procedure should approach the actual fluid that is in contact with the wastes in the landfill environment. Unfortunately, there is no way of developing a single leaching solution that represents all the varying conditions with regard to pH, oxidation-reduction potential (Eh), presence of chelating or complexing agents, etc. that might be present in a landfill. The general tendency in most investigations is to use an agressive leaching solution with low pH and low Eh to simulate a the worst case landfill environment.

Further practical restraints are placed on the composition because the test solution must be useful in an ordinary laboratory situation. Preparations that require handling under inert gases or that require reagents that cannot be obtained in an adequately pure form without great expense are not appropriate for a generalized testing system. Most investigators have selected weakly acidic solutions such as carbonic acid ($CO_2$-saturated water) or acetic acid as leaching media (3-7).

Use of these mildly acidic leaching solutions has its basis in the fact that natural precipitation and soil waters (which contain $CO_2$) are mildly acidic. Simple acetate buffer systems have long been used in estimating the availability of trace metals in agriculture. For example, Morgan's solution, an acetic acid-sodium acetate buffer, is routinely used to assess availability of metals in agricultural soils. To the extent that these mildly acid systems reflect increased solubility in rainwater or soil water, they represent the best compromise as a leaching medium. The groundwater in a landfill (especially in a landfill containing only solidified industrial wastes) may never reach the low pH observed in the acetic acid-based solutions, but roots growing down into the waste could possibly reduce the pH in their immediate vicinity to levels similar to those seen in acetic acid and acetate buffer solutions.

### Waste-to-Leaching-Solution Ratios--

The decision as to the ratio of waste to the amount of leaching solution is always a compromise. Obviously, a waste can come into contact with an enormous quantity of leaching solution (rainwater, groundwater, etc.) after disposal. Where the waste-to-leaching solution ratio is very large, (1:1 or 1:2), common ion effects can reduce the solubility of certain chemical constituents. Smaller waste-to-leaching-solution ratios (1:5, 1:40) are considered to be appropriate (3-6).

In most cases, the practical restraints on the testing require that a large enough volume of leaching liquid be used to allow the analyses to be performed at the low levels necessary to assure the health and safety of persons coming into contact with a leachate from the waste. Thus if a level of a toxic organic compound must be determined to part-per-billion levels, several liters of leachate must be available from the test procedure.

The ability to generate a relatively large volume of leachate by running tests in duplicate or triplicate is a very practical asset in the design of a testing procedure.

### Number of Elutions of Leaching Solution Used--

In most leachate testing, the initial samples of leachate produced can be considered to contain the maximum concentrations of potential contaminants that will be observed in the test procedure. The reason is that the initial leach liquid samples are exposed to the waste while the highest concentrations of soluble contaminants are present on the fresh waste surfaces. Also, the maximum amount of fine-grained solid material (which would have a greater inherent solubility because of its small particle size) is available in the waste during the first elution.

### Surface Area of Waste--

The ideal testing system would expose a leaching solution to the same surface area that it would be exposed to in a landfill. In the case of a dense impermeable waste material, this surface area could equal only the boundary surface of a waste monolith. In a loose, powdery material or a sludge, however, the surface area may be hundreds or thousands of times greater than the boundary surface of the waste mass.

One of the objectives of many waste solidification/stabilization systems is to produce a monolithic mass with a minimum surface area across which loss of pollutants can occur. Testing techniques that call for the waste to be ground to a powder destroy much of the advantage produced by solidification by these processes. However, some processes are designed to contain the waste even after being ground to a fine powder.

A compromise is to test the coherence of a solid waste by impact testing and to use the monolith or fragmented monolith as a test specimen. This approach offers the advantage of allowing a material that would not normally be landfilled in fragments to be tested in the configuration in which it has a minimum area for contaminant loss. The major disadvantages of such a physical and chemical testing system are that:

a. The exact stress that should be applied to fracture a coherent waste specimen as it might be fractured during landfilling or compaction cannot be accurately determined for all cases.

b. The surface area of the test specimen cannot be known with any precision after the specimen has been fragmented. This is important if rate of transfer of contaminant per unit surface area is to be considered.

c. Physical testing of solidified/stabilized materials indicates that wetting/drying and freezing/thawing cycles can produce rapid disintegration of many treated wastes. In many cases this fragmentation may be more complete than simply cracking the specimen in impact test apparatus.

d. The variation in fracture patterns between specimens of the same waste introduces another level of variability into the testing procedure and reduces the repeatability of the test.

### Agitation Employed--

The agitation of test samples during leaching or the stirring of the leaching solution has been advocated to permit more rapid equilibrium to occur between the specimen and the leaching solution. However, there is no real analogy in nature for an agitated leaching solution in contact with a solidified waste. In most cases where the waste would be landfilled, the water or leachate in contact with the waste would be stationary or flowing very slowly so that effective diffusivities characteristics are of prime importance.

The major objection to agitating or mixing the leachate and solid wastes is that mixing or shaking can grind the test specimen to smaller pieces, thereby increasing the surface area exposed to the leaching solution and invalidating the test.

### 3.5.2 The EPA Extraction Procedure (EP Toxicity Characteristic)

The EPA extraction procedure (EP) is the only leach testing system currently proposed by EPA as a definitive part of the procedure for the identification of hazardous wastes (3-8). Analysis of waste materials can be used to demonstrate the toxicity of wastes, but no simple test exists to show the degree to which these hazardous materials will be released into the surroundings. The goal of the EP is to determine the amount of contaminant that is released under circumstances approaching those that occur during the improper management of hazardous wastes. The EP involves exposure of the waste to a mild acid leaching solution. The EP can be considered an aggressive procedure for stabilized/solidified waste because it simulates the environment to which the wastes would be exposed if they were placed in a municipal landfill and saturated with landfill leachate. In cases where the stabilized/solidified wastes are cast in large monolithic masses, certain minor modifications of the test procedure are required. Details of the Extraction Procedure and its associated tests are discussed in Section 7.

## 3.6 EFFECTS OF BIOLOGICAL ATTACK ON TREATED WASTES

In long-term containment of treated hazardous and toxic wastes, biological attack can be a major problem. Biological attack can occur by direct utilization of some solidification material (such as UF resin) as a substrate for bacterial growth, or by the biological production of acid materials that can attack and corrode treated wastes.

Columbo and Neilson (3-9) approached the problem of possible direct biodegradation of solidification matrix materials by measuring the total amount of organic carbon released into leaching waters. Of the four solidification materials studied (Portland Type II Cement, Urea-Formaldehyde (UF) resin, asphalt, and vinyl ester-styrene) the UF resin showed the greatest problem with organic carbon release. In an 18-day leaching program, a 211.7 g sample released 4.48 g of carbon. No other solidification material approaches this carbon release. UF is generally conceded to be biodegradable.

Other biological reactions can affect solidified wastes indirectly. For example, if wastes containing metallic sulfides are incorporated in a cement matrix, reactions similar to those occurring in the production of acid mine drainage can occur. The sulfides can oxidize to sulfate and produce sulfuric acid, which can attack and dissolve concrete. This type of reaction occurs during the oxidation of pyrites and amorphous iron sulfides. Atmospheric oxygen is necessary for this reaction to proceed, and therefore such reactions typically occur at the top of the saturated zone in sulfide-rich landfills or waste piles.

Plant roots are another source of acid that can remobilize wastes. Root hairs typically discharge carbon dioxide into surrounding water and create a mild acid (carbonic acid) that is capable of putting many toxic metals into solution as bicarbonates. Organic acids released by decaying roots can also cause corrosion of some waste materials, particularly those solidified with a lime or cement-based process.

## 3.7 EFFECTS OF CURING AND AGING PROCESSES ON TREATED MATERIAL

Curing and aging processes affect various treated (solidified) wastes in widely different ways. Some polymeric materials add linkages during curing and become stronger and less prone to leaching. In other polymers, where the waste is not an integral part of the structure, separation of solid and aqueous phases can occur.

Examples of these different effects can be seen in the contrasts between cementitious (silicate) solidification systems and UF systems. Moore and others (3-10) demonstrated that for cementitious systems less leaching was observed when cement-based samples had been cured more than 100 days. The conditions of curing were also important. Specimens cured under humid conditions (where polymerization would be accelerated) were less leachable than samples that were allowed to dry during curing.

In contrast to cement-based systems, UF solidification results in the formation of a weep water that is not bound into the polymer structure. Aging of this material produces shrinkage and additional excess water (3-11). Containment of waste decreases with aging.

Other waste treatment systems that involve bitumen-based or water extensible polymer systems may also show long-term curing changes, but no data are currently available to demonstrate whether aging/curing effects will be detrimental to waste containment properties.

Obviously, where encapsulation systems use a surface coating of polymer, aging effects will be especially critical. If isolation depends on the integrity of a polyethylene or organic polymer jacket, any weaking or embrittlement will severely compromise waste containment (3-12).

Each proposed treatment system will require testing after aging to assure long-term waste containment.

## 3.8 ECONOMIC CONSIDERATIONS OF TREATMENT OPTIONS

Most waste materials that are currently being considered for disposal have no present value, and thus all solidification/stabilization costs represent additional expenses to be added to the ultimate cost of the product or service sold. A complete economic analysis must consider costs of waste transportation, materials and equipment required for stabilization/solidification, skill levels of treatment plant operators, fees or royalties for use of patented processes, and cost of transporting and landfilling treated wastes. This type of analysis often must be undertaken on a case-by-case basis. However, to obtain an initial impression of the usefulness of different waste treatment systems now and in the future, it is possible to restrict economic considerations to present and projected costs for materials, equipment, and energy. In most treatment systems, the cost of materials required is the major item regulating present and projected costs. Table 4-6 outlines the present and future economic considerations for major waste stabilization/solidification systems.

As shown in Table 3-6, the silicate-based systems (cement-based and pozzolanic) operate with the least expensive materials and have the most stable pricing structures for raw materials. The organic polymer systems (including bitumen) have the most easily disturbed raw material costs because the prices of raw materials used in these systems are tied to the price of oil. At present economic considerations appear to be heavily weighted toward low-temperature silicate systems and against organic polymers.

## TABLE 3-6. PRESENT AND PROJECTED ECONOMIC CONSIDERATIONS FOR WASTE STABILIZATION/SOLIDIFICATION SYSTEMS

| Type of treatment system | Major materials required | Unit cost of material | Amount of material required to treat 100 lbs of raw waste | Cost of material required to treat 100 lbs of raw waste | Trends in price | Equipment costs | Energy use |
|---|---|---|---|---|---|---|---|
| Cement-based | Portland Cement | \$0.03/lb | 100 lb | \$ 3.00 | Stable | Low | Low |
| Pozzolanic | Lime Flyash | \$0.03/lb | 100 lb | \$ 3.00 | Stable | Low | Low |
| Thermoplastic (bitumen-based) | Bitumen<br>Drums | \$0.05/lb<br>\$27/drum | 100 lb<br>0.8 drum | \$18.60 | Bitumen prices are rising rapidly because of oil prices | Very high | High |
| Organic polymer (polyester system) | Polyester<br>Catalyst<br>Drums | \$0.45/lb<br>\$1.11/lb<br>\$17/drum | 43 lb of polyester-catalyst mix | \$27.70 | Price could rise rapidly due to oil shortage | Very high | High |
| Surface encapsulation (polyethylene) | Polyethylene | Varies | Varies | \$ 4.50* | Price could rise rapidly due to oil shortage | Very high | High |
| Self-cementing | Gypsum (from waste) | ** | 10 lb | ** | Stable | Moderate | Moderate |
| Glassification/mineral synthesis | Feldspar | \$0.03/lb | Varies | — | Stable | High | Very high |

* Based on the full cost of \$91/ton.

** Negligible but energy cost for calcining are appreciable.

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# SECTION 4

# ASSESSMENT OF CURRENT DATA ON PHYSICAL AND CHEMICAL PROPERTIES OF TREATED WASTES

Recent interest in chemical stabilization of hazardous industrial wastes is beginning to bring about the accumulation of data from studies dealing specifically with these solidified waste products. Most information found in this section comes either from a few government-sponsored studies or from the vendors of waste treatment systems themselves. The results presented here are intended to be representative of the kinds of tests that are commonly performed and the ranges of data that are typically found. Many of the data have been transformed into common units to give uniformity and comparability to the results.

## 4.1 EXISTING DATA ON PHYSICAL PROPERTIES OF TREATED WASTES

Because no physical testing regime specific for solidified waste has been designed, most tests performed are those commonly used to determine the properties of soils and concrete. Thus, the test results do not always represent the best information needed to judge the containment capability of the treated waste, but they are useful in making comparisons with other materials whose properties are described in the literature. The incompleteness of the data and the variability in the testing techniques make correlation of physical properties with leaching characteristics very difficult. Correlations should be made only in cases where the physical properties are known to be determined on replicates of the actual samples used in the leaching test. Details of the typical test and interpretation of the results are discussed in Section 3.4.

Another important consideration in discussing the physical properties of treated wastes is that the physical properties that are important to the containment success of the different types of treatment processes vary greatly with the treatment type. For instance, the unconfined compressive strength of a treated product is meaningful only for those processes that limit contaminant loss by producing a solid monolith. Processes that produce soil-like or plastic, spongy masses or encapsulates require completely different testing regimes. Even typical soil tests such as Atterberg limits or undrained shear strength may not have an important bearing on containment properties of the soil-like products of some treatment systems. The physical tests that are indicative of treatment success are process-specific and must be determined for each individual case.

Unconfined compressive strength (or analogous measurements) and permeability are most commonly reported for the treatment processes that produce monolithic products for which high strength values and low permeabilities are said to be indicative of good containment. Compressive strengths of $10^5$ to $10^6$ N/$m^2$ and permeabilities of $10^{-5}$ to $10^{-6}$ cm/sec are not unusual for concrete-based treatment systems (Table 4-1). Organic admixture systems generally are plastic (with low strength) and vary from highly permeable to impermeable depending on the kinds and amounts of additives used. The treatments that produce clay or soil-like products cannot be tested using the physical testing procedures designed for concrete-like products. These products usually have relatively high permeability and depend on containing the pollutants by binding them inside a molecular matrix. A summary of the kinds of physical tests reported by the major vendors in the field are presented in Table 5-1 along with the process type and comments of performance in leach tests.

The details of the tests that are performed are quite important and should be indicated for each test made. Table 4-2 illustrates the changes in the unconfined compressive strength of samples of treated products made with varying amounts of cement and water content of the particular sludge being fixed. Note that a 10% to 15% change in the water content will change the compressive strength of the product several fold. Small changes in the amounts of impurities or the sludge pH can also have profound effects on the properties of the final product.

A comprehensive study of physical and engineering properties of treated and untreated flue-gas cleaning and hazardous industrial sludges has been performed by the U. S. Army Engineers, Waterways Experiment Station (WES) (4-1, 4-2, 4-3). The same treated and untreated sludge samples were also used in several leaching tests, some of which are still in progress. Five flue-gas cleaning sludges and five hazardous industrial sludges were treated by up to seven different solidification/stabilization vendors. The wide variety of final products made it difficult to choose which physical and engineering property tests to run. Physical property tests that could be run on all treated sludges were specific gravity, water content, void ratio, velocity, bulk unit waste, and dry unit waste. Tests for engineering properties included compaction, unconfined compression, modulus of elasticity, permeability, and durability. Wet-dry and freeze-thaw cycle tests were also performed. Results reported to date for the leaching tests on the same batch of samples indicate that none of the physical properties tested were of significant value in estimating loss rate in all leaching tests. The results of the physical tests appeared to useful only for predicting handling characteristics or disposal site requirements. The tests might be useful predicting the success of a specific treatment system on a particular waste type, but were not valid when comparing between treatment types.

## 4.2 EXISTING DATA ON CHEMICAL PROPERTIES OF TREATED WASTES

Results of leaching tests are commonly reported by vendors of waste treatment systems. However, the protocols of leaching tests vary widely, from a 1-hr unstirred, distilled-water leaching test on undisturbed treated waste samples to extended, repeated leaching of ground samples by aggressive leaching solutions. Some vendors report results of field tests. Table 4-1

TABLE 4-1. RESULTS OF PHYSICAL PROPERTY AND LEACHING TESTS MADE BY SLUDGE STABILIZATION VENDORS*
NOTE: THESE DATA ARE PROVIDED BY THE VENDOR COMPANIES FOR ILLUSTRATIVE PURPOSES ONLY AND ARE NOT VERIFIED

| Vendor or data source | Solidification basis | Physical property tests and results | Typical permeabilities (cm/sec) | Leaching tests and results |
|---|---|---|---|---|
| Atcor Washington, Inc. (Div. Chem. Nuclear Systems, Inc.) Peekskill, N.Y. 10566 | Cement | Numerous results available. Product is monolithic cement structure with no freewater | — | Numerous results available. Leaching rate found acceptable for shallow land burial. |
| Chemfix, Inc., Kenner, La. 70063 | Cement and soluble silicates | Treated material varies from soil-like to concrete-like monolith with high bearing capacity. | $10^{-5}$ to $10^{-6}$ | Extensive leaching tests have been run on a variety of processed materials. Tests run include cyclic leaching tests, saturation extraction tests, and nonequilibrium extraction systems. |
| Dravo Lime Co., Pittsburgh, Pa. 15222 ("Calcilox") | Cementitious product from basic, glassy blast furnace slag | Treated material dry with clay-like consistency (like compacted clayish soil). | — | Field leaching test results with FGD sludges available. Typically, leaching rates were reduced 1-2 orders of magnitude compared to untreated material. |
| Environmental Technology Corp., Pittsburgh, Pa. 15220 | Lime plus ion-exchange medium and binder | Product resembles clay in appearance and properties. Strengths average around 9.6 x 10 N/$m^2$. | $10^{-6}$ | Unique open trench leach test gave results (one of ten sludges) after 1 month 1-5000 mg/1 dissolved solids 5-800 mg/1 SO4, and less than 0.01 mg/1 of Ni, Mn, Cr, Fe, and Zn |
| I. U. Conversion Systems Horsham, Pa. 19044 ("POZ-O-TEC") | Fly ash and lime-based (pozzolanic) | Unconfined compressive strength (FGD sludges) >1.2 x $10^3$ N/$m^2$ | $10^{-5}$ to $10^{-7}$ after 2 to 4 weeks | The company maintains that forced leachate tests are not valid for their product. different tests have shown a reduction in concentration of most species in leachate of 1/2 to 1/200 that from untreated wastes. |
| Ontario Liquid Waste Disposal, Ltd (Canadian Waste Technology), Markham, Ontario, Canada L3R-1G6 | Silicate compounds | For cost reasons, end product is usually low-strength; but strengths up to 21 x $10^6$ N/$m^2$ are possible. | — | Heavy metal concentrations in leachate are commonly below 1 mg/1 from acid, metal-bearing, treated wastes. |
| Polymeric Materials Section, Department of Material Science, Washington State Univ., Pullman, Wash. 99164 | Polyester resin | 40% resin product has compressive strength of 15 x $10^6$ N/$m^2$ | — | Leachability after dissolution of surface materials is practically negligible. |

(Continued)

## TABLE 4-1. (Concluded)

| Vendor or data source | Solidification basis | Physical property tests and results | Typical permeabilities (cm/sec) | Leaching tests and results |
|---|---|---|---|---|
| Sludge Fixation Technology Inc., Orchard Park, NY 14127 ("Terra-Crete") | Self-cementing process for FGD sludges (calcination) | Strengths from $9.6 \times 10^4$ to $5.7 \times 10^5$ $N/m^2$ are possible depending upon proportions | $10^{-6}$ to $10^{-7}$ | Data on leaching of treated lead-rich FGD sludges shows less than 0.01 mg/l in leach liquid |
| Stabatrol Corporation Norristown, PA 19401 ("Terra-Tite") | Cementitious additives | Unconfined compressive strengths to $4.8 \times 10^5$ $N/m^2$ | $10^{-7}$ | "insignificantly low" |
| Stablex Corporation Radnor, PA 19087 ("Seal-o-safe") | Cement and Pozzolanic Materials | Strengths typical for grouts used as fillers and soil stabilizers, but much less than concrete | $10^{-7}$ | Grinding product to powder and immersing in water for 3 hrs gave very little (<1 mg/l) loss of materials |
| TJK, Inc. North Hollywood, CA 91605 | Cement | Strengths vary widely but 5-10 $\times 10^5$ $N/m^2$ are not uncommon with 20% (w/v) additives | — | Grinding product to powder and immersing in water for 6 hrs showed only low levels of pollutants were lost (or about 1 mg/l) |
| Todd Shipyards Corp. Galveston, TX 77553 ("Safe-T-Set") | Organic Polymer (not U-F) | — | — | Nine tests reported: Escape of radioactive material, temp. cycle, several immersion tests, off-gas tests, and biological and radiation stability |
| TRW Systems Group Redondo Beach, CA 90278 | Inorganic cements and polybutadiene resins | Tests include; mechanical testing, bulk density, surface hardness, compressive strength | — | Leaching tests at pH 3.8 to 4.0 and |
| Werner and Pfleiderer Corp., Waldwick, NJ 07463 | Bitumen encapsulation | Plastic solids usually placed in steel drums | negligible | Leach rates average 100 times less than comparable cement treated wastes |

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* Taken from EPA-600/2-79-056 and company literature.

TABLE 4-2. RELATIONSHIP BETWEEN PERCENT SOLIDS, UNCONFINED COMPRESSIVE STRENGTH AND CEMENT CONTENT OF A CHEMICALLY STABILIZED SLUDGE*

| Cement content % (w/v) | Sludge solids initial content % | | | |
|---|---|---|---|---|
| | 45.5 | 50.0 | 55.5 | 62.5 |
| 5 | 0.8 | 1.4 | 1.4 | 4.7 |
| 10 | 3.7 | 10.1 | 20.6 | 40.1 |
| 15 | 11 9 | 27.2 | 51.3 | 68.4 |
| 20 | 26.7 | 47.2 | 76.5 | 101.2 |

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* Data from information supplied by Takenaka Komuten Co., Ltd., Tokyo, Japan. Data in kg/$cm^2$ after 240 days curing.

lists typical types of leaching tests and results from the major vendors of waste treatment systems.

## 4.3 CORRELATION OF PHYSICAL AND CHEMICAL PROPERTIES

The great variety of treatment techniques makes it difficult to consistently correlate physical and chemical properties in treated materials. The asphaltic materials and the plastic-jacket encapsulates are imprevious solids and both show excellent waste retention. When admixes of wastes and pozzolan or Portland cement are attempted the results become less easily interpreted. Some admix systems depend on chemical binding and adjustment of pH, thus impermeability, increased strength and decreased void space are not as important as the chemical composition and potential binding reactions in the mix.

## 4.4 INTERPRETATION OF PHYSICAL AND CHEMICAL DATA

Interpreting the chemical and physical data collected on stabilized/solidified wastes is very complex. How much waste containment must a stabilized specimen exhibit? How strong physically must a treated waste material be? Absolute guidelines may be set, or the best judgment of regulatory officials may be used. Two major methods of data interpretation exist: Attempting to predict environmental impact, or using rigid standards for waste materials that ensure some degree of containment regardless of surrounding conditions.

No presently required chemical leach test is designed to predict the ultimate containment of treated toxic waste, but test protocols developed for the nuclear waste industry can be employed to model waste containment (4-4, 4-5, 4-6). The problem of radionuclear waste escape from solids formed using matrices of cement, asphalt, ceramic, or glass media can be modeled using expressions that take into account diffusion and concentration-dependent dissolution. Details of tests based upon the predictive International Atomic Energy Agency testing procedure are given in Appendix B and further discussion of predictive models is given in Section 6.

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## SECTION 5

## DESIGN CONSIDERATIONS FOR SOLIDIFIED AND STABILIZED WASTE DISPOSAL FACILITIES

Disposal of treated wastes is subject to the same regulatory and operational constraints and considerations as the disposal of any other waste stream, even though the end product is nonhazardous and/or easily managed or transported. This section addresses special aspects of treated wastes that may be important to the disposal operation, and the general aspects and alternatives of waste disposal under currently proposed regulations and technology. The major emphasis of this section concerns nonhazardous disposal technology and regulations under RCRA definitions and procedures necessary to avoid the more rigorous hazardous waste disposal requirements.

### 5.1 SPECIAL CONSIDERATIONS FOR HANDLING AND DISPOSAL OF STABILIZED/SOLIDIFIED WASTES

Chemical treatment usually strives to produce a solid monolith in order to exclude leaching waters from the bulk of the waste materials. The larger the treated waste block, the greater is the proportion of the waste that is isolated from environmental interactions. The treated waste may also require secondary containers such as drums or tanks. Some treated wastes present unique problems to the typical waste handling and compacting equipment designed for loosely packed refuse or semisolid sludges. The solid block should be formed and covered with a minimum of fracturing to retain the benefits of treatment.

A very common practice (especially for hazardous sludges) is to combine the treatment and disposal operation. In this method, the wastes are transported to the facility in their original (and perhaps hazardous) condition, where they may undergo chemical treatment. The wastes are mixed with the appropriate chemical additives and pumped directly to the waste disposal area as a semisolid slurry that solidifies in place into a single monolithic mass. As yet, no specific regulations have been written concerning this type of operation, but it appears that if hazardous wastes are involved, the treatment phase of the operation would be covered by the more rigorous hazardous waste regulations with regard to storage and treatment operations.

All treated wastes are susceptible to breakdown and release of the contained wastes if they encounter an aggresive environment in the waste disposal site. Even mildly acid environments will slowly breakdown most cement- and pozzolan-treated wastes. High sulfate concentrations in the contacting waters will cause surface spalding and structural breakdown of cement-based products. Organic solvents, and even oils and greases, can cause loss of integrity in asphalt-based treated wastes. Strong oxidants can cause breakdown of many organic-based treated wastes. Even glass-containing wastes can be etched and devitrified in strongly alkaline environments.

Sanitary landfills are currently being studied as depositories of non-hazardous treated wastes, since they represent a common and well understood disposal system (5-1). Although long-term results are not available, it now appears that the increased rate of dissolution of the cement- and pozzolan-treated wastes is more than offset by the large exchange capacity of the cellulosic residue in the municipal waste. Little heavy metal release to the surrounding environment occurs. Attenuation of the pollutants by the municipal refuse may be only temporary however, since after the bulk of the organic material is broken down, release may occur. Sanitary landfills are best presumed to be unsuitable for disposal of treated wastes.

## 5.2 DESIGN FACTORS FOR HAZARDOUS WASTE LANDFILLS

Treated wastes that meet the EPA criteria for hazardous waste must be disposed of in a landfill that has been designed and approved for handling hazardous solid waste. In general terms, hazardous waste landfills must provide complete, long-term protection of the quality of surface and subsurface waters from any of the hazardous constituents disposed therein and from any hazards to public health and the environment. Such sites must be located or engineered to avoid direct hydraulic continuity with surface and subsurface waters. Subsurface flow of groundwater into the disposal area must be prevented. Leachate generation should be avoided; any produced must be collected and treated. Monitoring wells must be installed, and a sampling and analysis program must be designed and approved. These requirements would also be desirable for typical, sanitary landfills. The primary difference involves the degree of concern and care, and the record keeping that must be involved where hazardous materials are involved.

The state of the art for predicting discharges or releases from landfills is poor. Therefore EPA states in their proposed rules that the only option available to insure protection of human health and the environment is to prescribe design and operating standards for hazardous waste landfills that provide maximum containment. An inert, essentially impermeable liner is required at all hazardous waste landfills. Furthermore, in localities where climatic and natural geologic conditions are such that leachate buildup might be expected (where evaporation does not exceed precipitation by 20 in. or more), an active leachate collection system is required so that any leachate generated can be removed and treated. Landfills located over an underground drinking water source must install groundwater and leachate monitoring systems and provide for up to quarterly sampling and analysis of specified parameters. Sampling, analysis, and record keeping are required for at least 20 years after closure of the landfill. Exact location of each hazardous waste (with respect to permanently surveyed benchmarks) and the dimensions and compositions of the waste must be recorded and kept available for inspection.

EPA has proposed to restrict hazardous waste landfills from accepting ignitable, reactive, or volatile wastes, or wastes that are bulk liquids, semisolids, or sludges. Liquid wastes in containers are prohibited but liquids may be solidified in the container. Bulk liquids can be fixed to meet regulations.

## 5.3 USE OF LAND TREATMENT OF BIODEGRADABLE INDUSTRIAL WASTES

Landfarming incorporates biological, chemical, and physical processes of the upper soil horizons to effectively treat biodegradable industrial wastes. Selection, deposition, and postdepositional care must be administered to maximize the effectiveness of waste degradation. Disposal of hazardous waste by landfarming may require pretreatment to eliminate combustion, reaction, or volatilization hazards. Such treatment must result in waste attributes conducive to the landfarming degradation processes.

Similarities between this recycling of waste products and agricultural farming all depend on planning and readily available, dependable, large-scale equipment. Combined agricultural techniques and landfarming of wastes can result in improved land surface and soil characteristics, but the primary objective is to dispose of waste continuously while maintaining or improving the soils disposal efficiency for long-term usage.

The densities and makeup of microbial populations vary with soil depth and geographic location. Geographic location also affects the seasonal duration and intensity of microbial activity. The surface or near-surface deposition of waste materials and mixing by conventional plow techniques exposes concentrated waste material to large populations of microbes.

Whether waste material is deposited on or beneath the soil surface is determined by many factors such as the character of the waste, the microbes, and the soil. The function of the created waste-soil system is to produce harmless volatiles, water soluble components, and decomposition products available for uptake by vegetation. Absorption of waste components by mineral constituents of the soil must be avoided or the storage capacity will eventually be reached and waste will be transmitted to groundwater systems. Depending on future site use, the landfarm can become a repository of nonbiogradable materials, although such is not the purpose of a landfarm. Pretreatment could provide nonbiodegradable material in a fixed form, possibly improving soil texture.

Although the interactions among the soil constituents and waste materials are complex, a list of general factors is given as follows:

Temperature
Moisture content
pH
Inorganic nutrients
Oxygen availability
Chemical composition of wastes
Physical characteristics

The requirements for landfarming delineate environmental concerns primarily related to water quality. The landfarm must not have direct contact with surface water or groundwater systems. Erosion problems are generally not associated with landfarm areas because of restrictions posed by surface slope requirements. However, any direct exposure of waste materials by erosion must be considered. Subsurface geology must prevent possible groundwater contamination. The surface slope must be sufficiently steep to prevent ponding, but it must be gentle enough to prevent erosion. The soil pH must be above 6.5 to prevent leaching of toxic metals. Soil characteristics throughout the site must be ascertained before, during, and after the site is in active use. This requirement establishes that the soil has been returned to an equivalent preexisting condition before closure. Ignitable, reactive, volatile, and incompatible wastes are not permitted in a landfarm disposal system. Some treated waste may prove to be suited to landfarming if release of degradable compounds occurs at a rate comparable to their destruction. The technical resource document on Design and Management of Hazardous Waste Land Treatment Facilities (5-2) should be consulted for further detail.

## 5.4 OPERATION AND MANAGEMENT OF DISPOSAL FACILITIES FOR TREATED WASTES

Many of the listed operational procedures discussed below are not now required for waste disposal facilities that are permitted to accept only nonhazardous waste. However, because most treated wastes would be categorized as hazardous if they were not treated, procedures suitable for hazardous waste should be followed insofar as possible. In the case of long-term instability of the treated product, such precautions may prevent environmental or groundwater degradation in the vicinity of the disposal site. Most procedures protect the operators of the disposal site as well as the general public, and they can be accomplished with relatively small expense. EPA's position at this time is that treatment of any kind does not reduce the need for a complete monitoring program.

### 5.4.1 Monitoring of Ground and Surface Waters

The most frequent and serious environmental impact in the disposal facility is also the most easily overlooked and most expensive to rectify--that of losing leachate and pollutants to the groundwater. Monitoring of the groundwater quality to ascertain whether pollutants are being lost from the disposal sites is the only method to be certain that no hazardous constituents are being lost. Monitoring should begin before opening of the site to provide baseline data on the water quality in the area. Ideally, background samples should be taken throughout all hydrological seasons, as considerable variation can occur within the year.

Monitoring wells should be placed both up and down the groundwater gradient from the disposal site. Changes in the overall groundwater quality in the area would not be seen equally in water samples from all wells. Pollutants from the disposal site itself should only show up in the water samples from wells down the groundwater gradient.

Any elevated or abnormal concentrations should immediately be double-checked with new water samples so that immediate remedial action can be taken. A quick response to stop the source of the leachate infiltration is always cheaper and more effective than efforts at cleaning up an aquifer after extensive pollution has occurred.

### 5.4.2 Gas Monitoring

Landfills containing putresable materials produce large amounts of methane and carbon dioxide. Other gases (hydrogen, ammonia, hydrogen sulfide, etc.) can be produced in appreciable quantities from particular wastes typically found in some landfills. These reactive gasses can migrate and attack treated wastes causing a greatly increased loss of constituents. Depending on the geology and soil permeabilities at the site, gases can migrate long distances underground and accumulate under any structures on or near the disposal site. Explosive gases, especially methane, should be monitored. Toxic or asphyxiating gases should also be monitored on a regular basis with appropriate instruments. The presence of such gasses should bring about a reassessment of the containment properties of the treated wastes.

Gas migration through the soil is especially prevalent in sandy, permeable soils and in rainy periods as the influx of rainwater into the soil forces gases into the surrounding areas. Landfill gases are elusive, and concentrations can vary greatly at the same sampling point over the course of a few hours or between simultaneous sampling at two adjacent sampling points. Areas with stunted or dying vegetation should be checked as likely areas of gas migration and/or collection.

## REFERENCES

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5-2. Brown, K. W. 1980. Design and Management of Hazardous Waste Land Treatment Facilities. SW-874. Office of Solid Wastes, U. S. Environmental Protection Agency, Washington, D.C. In press.

# SECTION 6

## STEPWISE EVALUATION OF STABILIZED/SOLIDIFIED WASTES

In any waste disposal operation that involves a treatment such as stabilization/solidification applied to a waste and ultimate land disposal of the solid product, a number of considerations immediately arise:

a. Is the waste still ignitabile, reactive, or toxic?

b. What is the maximum toxic hazard presented by the solidified waste under normal conditions?

c. Will the stabilized/solidified material remain in a solid condition (with low permeability) in the disposal site?

d. What is the best estimate of leach losses over a long term (i.e. 100 years)?

e. What are the operating plans at the site selected?

All of these questions are important in judging the acceptability of a hazardous waste disposal operation. Unsatisfactory answers to any one of these questions would require revision of the disposal program.

The evaluation procedure outlined in this section uses examples from a common case--disposal of a waste that has been treated using a cement-based or pozzolan system for shallow land burial. The procedure outline may require modification for other treatment systems where plastic incorporated waste materials are produced or where secondary containers such as drums are employed. Parts of this section are based upon EPA's Hazardous Waste Management System; Part III, Identification and Listing of Hazardous Waste (6-1).

## 6.1 STEP 1. EVALUATION OF HAZARDOUS NATURE OF TREATED WASTE

### 6.1.1 Determination of Ignitability.

To be classified on non-hazardous, the treated waste must not be ignitable and must not cause fires through friction, absorption of moisture, or spontaneous chemical changes nor burn persistantly or vigorously. If any free liquid is present in the sample, the liquid must pass the test procedure outlined in ASTM Standard D-93-79 or D-3278-78. The waste is classified as hazardous if it has a flash point less than 60°C. If gases are evolved from the treated waste, they shall not be ignitable as determined by 49 CFR 173.300.

Example: If a waste hydrocarbon is to be blended into a cement mix, ignitability tests should be run on any liquid or supension associated with the treated wastes. Solid samples of the treated waste should be tested to determine if a sustained fire is possible when the wastes are ignited. The Pensky-Martens Closed Cup Tester (ASTM D-93-79) is particularly suited to working with suspensions of solids and materials that form fumes when heated. Sustained burning of treated solid material can be judged using results from tests such as ASTM F 501. Data from ASTM F 501 should include flame time, glow time, drip flaming time, and burn length.

### 6.1.2 Determination of Corrosivity.

Any liquid associated with treated wastes must have a pH equal to or greater than pH 2 and equal to or less than pH 12.5 (6-2, 6-3). Treated materials must not corrode steel (SAE 1020) at a rate greater than 6.35 mm (0.250 in.)/yr at a test temperature of 55°C (130°F) as determined by the National Association of Corrosion Engineers Standard TM-01-69 (6-3).

Most cement or pozzolan-based treatment systems will maintain a pH near 12.5 in any associated liquid due to the calcium hydroxide present in the additives. The pH of a saturated aqueous solution of calcium hydroxide at 25°C is 12.4. Therefore it would be possible for any liquid associated with treated material to fail this corrosivity test. The pozzolan or cement-based treated material might only be acceptable under the corrosivity standard if no free liquid is present.

### 6.1.3 Determination of Reactivity.

To be classified as non-hazardous the treated waste should be normally stable and not undergo violent chemical changes. Materials that react with water will obviously have reacted during processing using cement or pozzolan incorporation. Compounds that are normally reactive will be diluted; but in general will remain reactive. Under the alkaline conditions involved in cement incorporation, sulfides and cyanides will not normally decompose, but if later exposed to acid groundwater, hydrogen sulfide or hydrogen cyanide gas can be produced. Both of these materials would be inappropriate for pozzolan or cement incorporation. Solutions with high concentrations of ammonium compounds can decompose to produce ammonia gas in a strongly alkaline environment. These materials may present problem during processing and disposal of treated wastes.

Materials that are explosive, oxidizers or autopolymerizable substances should also be disallowed in treated wastes. The Explosive Temperature Test (40 CFR 250.13) could appropriately be applied to treated wastes where explosive potential is suspected. Treated wastes that contain materials unstable to mechanical shock will, although diluted, can retain their instability in the blended product. Bureau of Explosives impact testing

(49 CFR 173.53(b), (c), (d), and (f)) could be appropriately used for testing treated wastes.

### 6.1.4 Determination of EP Toxicity

The standard EPA Extraction Procedure (EP) and maximum acceptable contaminate levels are outlined in reference 6-1. The list of contaminants represents only the minimum requirement at this time and therefore does not include many other potentially dangerous materials that might be present in the incorporated wastes. The analytical requirements should be selected to suit the specific wastes blended into the treated solid. For example, electroplating wastes commonly contain degreasing compounds and phenolics. It would be appropriate to look for these materials in the extracts from any treated electroplating sludge.

The extraction procedure is not efficient in assessing the loss of every contaminant. Organic contaminants may not be efficiently extracted from all matrices. Where serious organic contamination is suspected, additional testing using a variety of leaching solutions would be prudent.

## 6.2 STEP 2. DETERMINATION OF MAXIMUM TOXIC HAZARD UNDER NORMAL CONDITIONS

Because the solidified waste is to be landfilled, it will be exposed to rainwater, soil water or possibly even groundwater (assuming the water table could rise into the landfill). The surrounding water could become saturated with respect to any toxic or noxious compounds present as the wastes.

In order to discover if the waste can release objectionable levels of toxic substances, a maximum possible concentration (MPC) type of test can be performed. The solid sample is dried and ground to a powder ( 200 mesh). The ground sample is shaken or stirred in smallest practical volume of distilled water (at 20°-25°C) until the concentration of potentially toxic constituents no longer increases in the solution in contact with the waste. If it is suspected that a very soluble toxic material is present in the ground waste; the solution should be removed and placed in contact with a fresh (unleached) aliquot of ground waste. The goal of this type of test is to determine as nearly as possible what concentration of toxicants can be expected in water saturated with respect to the compounds in the waste.

An example of an effective MPC test protocol used in Harwell Laboratories (U. K.) is given in reference (6-4). The Harwell testing procedure is a multiple shake test that uses a minimum amount of leachate to assure that a saturated condition is produced in the liquid. Such tests represent a worst-case situation. Materials that can show very low concentration of potential pollutants would rank well in selection of treated materials for disposal.

## 6.3 STEP 3. DETERMINATION OF PHYSICAL INTEGRITY AND DURABILITY

In many stabilized/solidified wastes the containment properties depend on limiting the surface area across which transfer of potential pollutants can occur. Physical testing systems are required to judge the durability of the solidified waste.

Physical testing of waste materials becomes very important where the conditions for shallow land burial are not ideal. For example, durability testing is important where cover will not be sufficient to prevent cyclic wetting and drying, or freezing and thawing. If the cover is permeable, all of the containment for the waste may depend on the production of an impermeable monolith. However, for treated materials that can be ground to a powder and still not lose materials to leaching as in the MPC testing, the durability tests would be important only for structural integrity and would have little meaning for containment characteristics.

Physical properties testing is covered in Section 3. In general the stronger, more impermeable, and durable a treated waste, the more effective will be its containment. If the material does not fragment to create dust or increase the surface area for exchange, losses will be minimized. Cement-based treated wastes can be prepared with properties that approach commercial concrete. Tests have shown compressive strengths up to 2500 lbs/ sq in., with excellent durability, permeabilities of $7.9 \times 10^{-4}$ cm/sec and less than 20 % weight loss after 12 freeze-thaw cycles (6-4). Column leach testing has shown that in cement-based systems the strongest material, has the minimum contaminant loss (6-6).

Where the maximum possible concentration tests show potentially hazardous levels of toxicants, durability would have to be very high to demonstrate that physical characteristics of the material will prevent this "worst case" situation from occurring.

## 6.4 STEP 4. ESTIMATION OF LEACHING LOSS OVER A LONG TERM

Stabilized/solidified waste is meant to be landfilled and to remain buried indefinitely. In cases where infiltration is minimal and dilution of any potential leachate occur, no contamination from the waste will be detectable.

When solidified wastes are buried the major factor limiting the loss of material from the monolithic mass is diffusion of the chemical constituents to the surface of the solid. The rate of solution of material at the surface is large compared to the diffusion rate. Diffusion in a solid can be assessed using tests such as the Uniform Leaching Procedure (ULP) given in Appendix B. The results of the ULP are given as effective diffusivities (measured in $cm^2$/sec).

Effective diffusivities or leachability constants can be used an comparing the containment afforded by different solidification systems and for predicting the long-term losses from masses of wastes (6-7). Very little information is available on effective diffusities of solidified industrial wastes. Johnson and Lancione (6-8) presented some data on diffusivities of stabilized/solidified arsenic wastes; but the testing protocol used varied significantly from the standard system. Most data on leachabilities of solidified waste come from nuclear waste treatment. Usually the elements and the types of material treated differ greatly from typical industrial wastes. In general, glass-fused wastes have had lower loss rates then plastic (bitumen) encapsulated materials and plastic (bitumen) materials have lower loss rates than cement-based materials (6-9). Determining effective diffusinities is the best documented system for comparing the retention of different constituents of waste using the same solidification system as for comparing the containment produced by different solidification systems on one waste.

Diffusivities for different constituents can also be used to model the long-term loss of specific materials from solidified waste materials that have known shapes and dimensions. Details of modeling are given by Anders, Bartel, and Altschuler (6-7). If the size and shape of a waste mass are known and if it can be assumed that diffusion into a very dilute solution is the principal transport mechanism, a model for the loss of individual constituents can be set up. Figures 6-1 and 6-2 give the calculated retention rates for cylindrical barrel-size ingots and for flat slabs (10 cm thick) for 100 years for materials having diffusinities ranging from 1 x $10^{-5}$ to 1 x $10^{-12}$.

For example, if a cement-solidified cadmium waste were being evaluated, results from the ULP can be used to select an appropriate curve. If the wastes are solidified in drums, the appropriate diffusivity curve from Figure 6-1 would be selected and the percent loss of cadmium from a single ingot could be estimated. A steel drum would normally last 15 years so solution losses could be estimated from a point 15 years from the time of burial when the solidified waste would be exposed. Similarly Figure 6-2 could be used to predict waste losses from a semi-infinite slab of waste 10 cm thick. Other waste configurations can be modeled from equations available for less common shapes such as spheres or parallelepeds, etc. (6-7).

## 6.5 STEP 5. ASSESSMENT OF LAND BURIAL SITES

Other manuals in this series have examined performance of land burial sites and should be consulted (6-10, 6-11). In the case of treated wastes where designs call for creating low permeability monoliths, the escape of potential contaminants has been assumed to occur principally along the surface of the emplaced mass. If the physical properties of the waste indicate a durable final material, a maximum escape rate for contaminants based on the surface area of the emplaced waste mass can be estimated. This would be a maximum rate that would assume a maximum diffusion gradient (6-7). Other procedures such as estimation of percolation rate from cover parameters and examination of liner and drain performance would procede as with landfills designed to receive untreated wastes.

## 6.6 STEP 6. EVALUATION OF MONITORING AND CLOSURE PROGRAMS

Monitoring and closure of a solidified hazardous waste site would be similar to any other hazardous waste facility. Manuals for assessing these

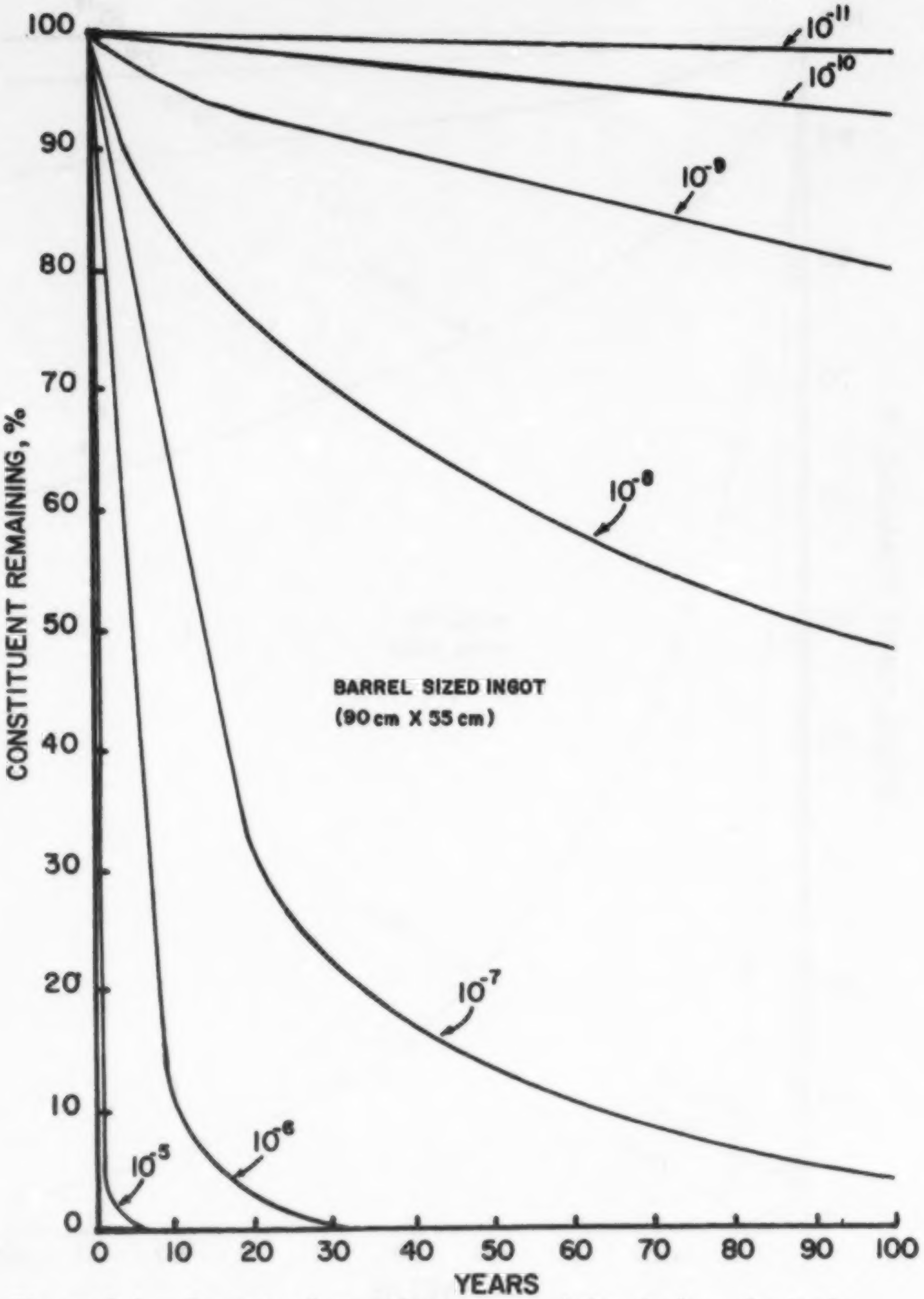

Figure 6-1. Percent of constituents remaining in barrel-sized, cylindrical ingots (90 cm long x 55 cm diam) of solidified waste over 100 years of leaching for wastes having diffusivities of $10^{-5}$ to $10^{-11}$ $cm^2$/sec

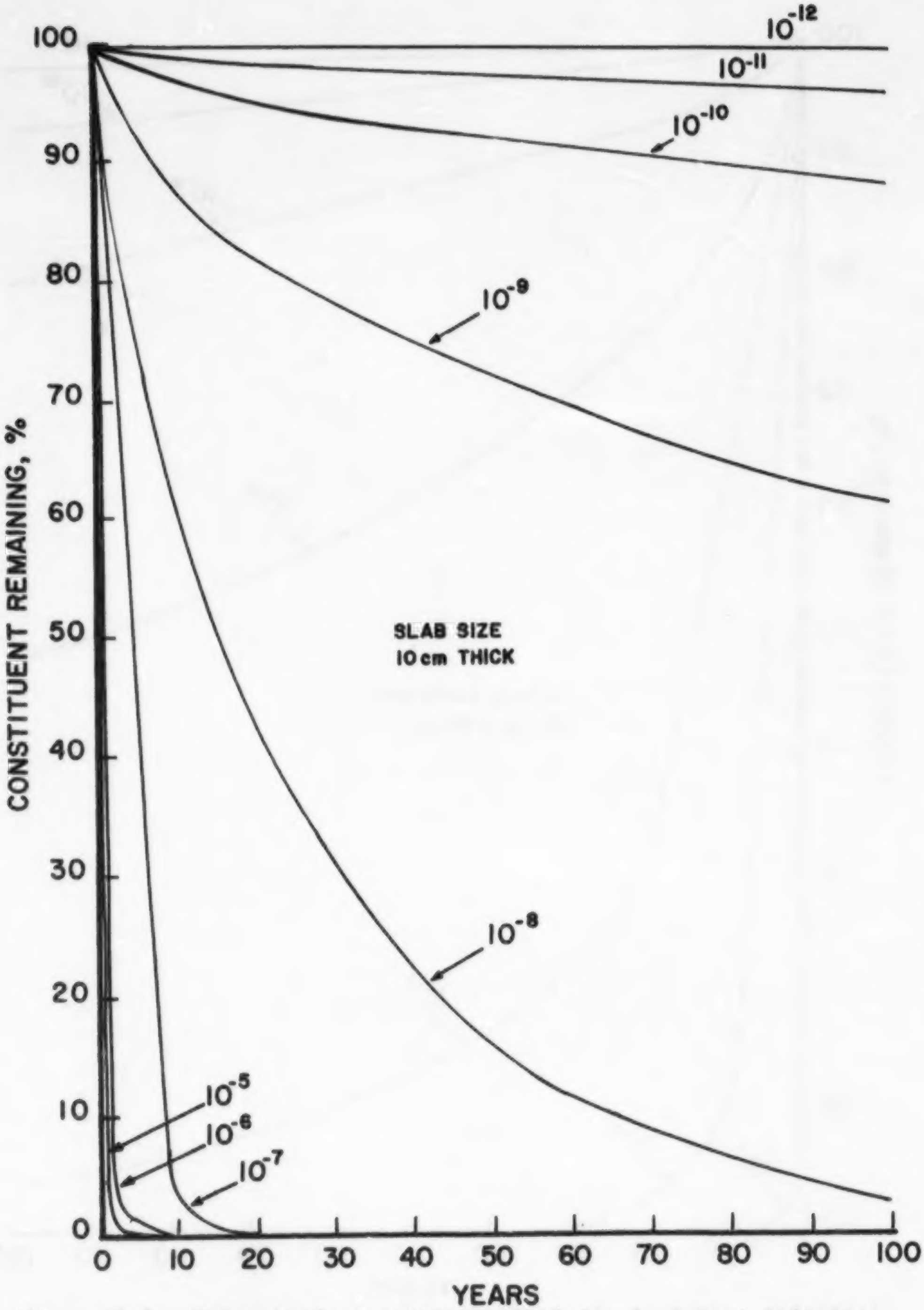

Figure 6-2. Percent of constituent remaining in a semi-infinite slab (10 cm thick) of solidified waste over 100 years of leaching for wastes having diffusitities of $10^{-5}$ to $10^{-11}$ $cm^2$/sec.

aspects of landfill design should be consulted. If the treated wastes were classified as non-hazardous by EPA, then closure of the facility would be no different than any other waste disposal area.

## 6.7 STEP 7. QUALITY CONTROL OF WASTE TREATMENT

Treated waste material may vary greatly from batch to batch due to variation in wastes incorporated or the conditions of treatment. In cement or pozzolan-based systems, small amounts of interfering materials can reduce strength, durability and chemical containment drastically. In some solidification operations in which the material is poured out to solidify as a monolithic mass, solidification may not occur and if an additional layer is poured over the unsuccessfully solidified wastes, a highly leachable zone in the waste mass is created. Such poor operating practices should be avoided.

Any treatment process should include a system for determining the character of the treated waste and a provision for reprocessing the material before final deposition if the treatment process was unsuccessful. The exact sampling pattern for determining treatment quality would depend on the variability of the feedstock for the treatment system and the quantity of waste treated. In batch operations, each separate batch should be leach tested and tested to determine selected physical properties. In a cement- or pozzolan-based system, any large changes in set-time or texture of the treated waste should be cause for a more complete testing sequence. Sampling procedures are outlined in references on industrial sampling designs (6.12).

## 6.8 STEP 8. EVALUATION OF AGED MATERIAL

Periodically samples should be cored from aged solidifed wastes to determine if breakdown and loss of contaminants has occurred. If the physical properties, strength and durability have not decreased and the permeability of core materials has remained low, the assumption of a low-permeability monolith of waste is justified. Leach testing of core material can be used to ascertain any decrease in containment properties with age. If a landfill operation can demonstrate that the treated waste is not breaking down, longer periods can be permitted between resampling of treated waste. For example in the first year of operation one core per 1000 cubic meters volume might be judged adequate. If the sample appears uniform and unchanged the core requirement could be halved.

## 6.9 PERMITTING AND OPERATING EXPERIENCE

There are at present few long-term records for operating hazardous waste landfills where treatment is being employed. Only small amounts of treated wastes have been emplaced at various manufacturing localities in the United States. Where these sites have been investigated, no major contamination of groundwater or sub-waste soil has occurred (6.13, 6.14). The lack of experience with treated wastes and the potential for application of treatment processes to inappropriate waste dictates that caution be exercised in granting permits.

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6.3. U. S. Environmental Protection Agency. Methods for Chemical Analysis of Water and Wastes. EPA 600/4-79-020, Environmental Monitoring and Support Laboratory, U. S. Environmental Protection Agency, Cincinnati, Ohio, 1979. 1970. 298 pp.

6.4 Wilson, D. C., and S. Waring. The Safe Landfilling of Hazardous Wastes. Paper presented at 3rd Int. Industrial Waste Waters and Waste Congress, IUPAC, Stockholm, Sweden, Feb, 1980. 14 pp.

6.5. Bartos, M. J., and M. R. Palermo. Physical and Engineering Properties of Hazardous Industrial Wastes and Sludges. EPA 600/2-77-139. U. S. Environmental Protection Agency, Cincinnati, Ohio, 1977. 89 pp.

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6.8. Johnson, J. C., and R. L. Lancione. Assessment of Processes to Stabilize Arsenic-Laden Wastes. pp. 181-186. In: Disposal of Hazardous Wastes. EPA-600/9-8-010. Environmental Protection Agency, Cincinnati, Ohio, 1980.

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6.10. Moore, C. H. Landfill and Surface Impoundment Performance Evaluation Manual. U. S. Environmental Protection Agency, Cincinnati, Ohio. (in press).

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6.13. Mercer, R. B., P. G. Malone, and J. D. Broughton. Field Evaluation of Chemically Stabilized Sludges. pp 357-365. In Shultz, D. W. (ed.). Land Disposal of Hazardous Wastes. EPA 600/9-78-016. U. S. Environmental Protection Agency, Cincinnati, Ohio, 1978. 453 pp.

6.14. Jones, L. W., P. G. Malone, and T. E. Myers. Field Investigation of Contaminant Loss from Chemically Stabilized Sludges. Presented at Sixth Annual EPA Solid and Hazardous Waste Research Symposium, Chicago, Illinois, March 17-20, 1980. 15 pp.

# APPENDIX A

## SOURCES OF FIXATION TECHNOLOGY

The data in this appendix were obtained from: Environmental Laboratory, U. S. Army Waterways Experiment Station. Survey of Solidification/Stabilization Technology for Hazardous Industrial Wastes. (EPA-600/2-79-056. U. S. Environmental Protection Agency, Cincinnati, OH. 1979.) Addition and changes contained in this appendix are from new communications from vendors.

NOTE: All information given in Appendix A has been taken directly from vendor literature and sales brochures. No attempt has been made to verify or interpret any vendor claims. This listing is given for illustrative and informational purposes only and should not be used for design or permit functions.

a. Name of Vendor: Atcor Washington Inc.
Division of Chem Nuclear Systems, Inc.
Park Mall
Peekskill, NY 10566

Contact: M. Brownstein, Director
(914) 739-9000

b. Category of fixing process: The process is classed as a masonry-based solidification systems (using cement).

c. Types of wastes treated: System is primarily designed to effectively solidify typical wastes from both boiling water reactor and pressurized water reactor nuclear power plants (which include 25% $Na_2SO_4$, 12% $H_2BO_3$, bead type ion exchange resin and various filter media - solka floc, diatomeccous earth and filter aid). The Atcor Radwaste Solidification System includes an in-line mixer/feeder which fills any size container, permits inclusion of bulky items and flushes clean with a minimum of water. All operation procedures are remote and/or automatic.

d. Types of waste excluded from treatment: sludges which do not combine with cement could not be handled, however, testing for specific sludges is required to ensure application suitability.

e. Cost of fixation: Cost is variable depending upon waste to be treated. Dry masonry cement is added up to volume equal to the volume of waste which gives final product about 130% of volume of original waste. Cement cost is approximately 9 cents per kilogram, but capital expenditure, transportation and personnel costs will vary greatly with the individual job.

f. Leach and strength tests: Leach and strength studies showing product acceptability for cement-based radwaste systems are numerous. The product is a monolithic cement structure exhibiting no free water and an acceptable leach rate for shallow-land burial.

g. Examples of past applications and current contracts: At present the Atcor system is used solely within the commercial nuclear power industry, however, studies are currently under way to use system for solidifying arsenic wastes and incinerator-generated wastes. Radwaste solidification systems have been purchased by 11 major power companies including: Northern States Power Company (Monticello and Prairie Island), Wisconsin Public Service Co. (Kewanee), Wisconsin Electric and Power Co. (Point Beach), Tennessee Valley Authority (Bellefonte), Taiwan Power Co. (Chin-Shan and Kwosheny), Duquesne Light Co. (Beaver Valley), and others.

a. Name of Vendor: Chemfix, Inc.
1675 Airline Highway
Kenner, Louisiana 70062
or mail correspondence to:
P. O. Box 1572
Kenner, Louisiana 70063

Contact: M. W. Duncan, President
(504)729-4561

b. Category of fixing process: Inorganic chemical additives (cements and soluble silicates) are mixed with the wastes to produce a gelling reaction that is followed by hardening. Mobile treatment plants that can each handle 1,000,000 liters/10 hour shift are provided. The process is also applied in fixed installations. The additives consist of less than 5% up to 10% by volume of the waste. The process varies with the percent solids and nature of the wastes. Generally the higher the percent solids the lower the additive requirement.

c. Types of wastes treated: Most types of waste can be accepted for this processing. The additives react with polyvalent metal ions producing stable, insoluble, inorganic compounds. Nonreactive materials (e.g. certain organics and asbestos) are physically entrapped in the matrix structure resulting from the reaction process. Process is usually custom designed for each type of waste.

d. Types of waste excluded from treatment: Some wastes containing certain organic compounds and/or toxic anions are not normally treated, however, in some such cases, specified pretreatment will allow solidification/fixation.

e. Approximate cost of processing: Varies greatly with the % solids and nature of the waste. Laboratory testing to determine cost is provided. Reagent costs would typically fall in 1 to 5¢/liter range with processing costs depending upon site conditions and location.

f. Data on leach and strength tests: extensive leach tests have been run on a variety of "processed" material and are available from the company. Data available includes results of cyclic leach tests, saturation extraction tests and non-equilibrium extraction systems. Acceptable leaching results have been obtained from a variety of industrial and municipal wastes. The strength of fixed material varies with the amount of additives used and the nature of the sludge. The fixed material can vary from a soil-like mass to a solid (concrete-like) monolith with high bearing capacity.

g. Examples of past applications and current contracts: The patented "CHEMFIX" process has been applied to the following wastes: chemical and allied products (160 x $10^6$ liters), petroleum refining (105 x $10^6$ liters), transportation equipment (88 x $10^6$ liters), primary metals (18 x $10^6$ liters), municipal waste water treatment, flue gas desulfurization wastes, dredging spoils, and radioactive wastes.

"CHEMFIX" is a registered trademark of Chemfix, Inc.

a. Name of Vendor: Dravo Lime Company
650 Smithfield Street
Pittsburgh, PA 15222

Contact: C. J. McCormick
(412) 566-4433

b. Category of fixing process: Dravo Lime Company's solidification additive, Calcilox, is a dry, free flowing, light grey-colored powder of inorganic origin. It is hydraulically active and when added to the slurry improves its handling and ultimate land disposal characteristics by imparting structural integrity to the settled slurry. The process could probably best be classed as pozzolanic or cementitious.

c. Type of waste treated: Calcilox is applicable to all calcium-based $SO_X$ scrubber waste as typically produced from coal-fired utility scrubbers. Calcilox is also applied to many inorganic mineral processing tailings that contain a large percentage of silica and alumina. Typical applications are on fine coal preparation wastes and uranium mill tailings.

d. Type of waste excluded from treatment: Sludges containing organics and sewage wastes cannot be treated.

e. Approximate cost of processing: The weight percent of Calcilox additive dosage ranges from 5 to 15% of the dry slurry solids weight. Low dosages (5-10%) are used with mechanically dewatered wastes (55 to 70% solids) and higher dosages (10-15%) with lower solids slurries such as thickener underflows with 25 to 35% solids. Costs are site and process dependent: no firm estimates are available.

f. Data on leach and strength tests: Leach data are available from field tests on flue gas cleaning waste and indicate reduced leach rates when compared to raw sludges. Typically, leaching rates are reduced one to two orders of magnitude below untreated wastes. The strength of the product is controlled by the mixing ratios, but the product has a dry, clay-like consistency similar to compacted clayish soil.

g. Examples of past application and current contracts: Extensive experience has been gained through contracts with several large power plants such as the Bruce Mansfield Power Station in Shippingport, PA, the Duquesne Light Company Phillips Power Station, and Allegheny Power Service Company's Pleasants Station. Current coal waste applications are at several large American Electric Power Company mines and at smaller independent operations in Ohio and West Virginia. Ongoing tests are being conducted with several uranium producers in the western United States under a Department of Energy contract.

"Calcilox" is a registered trademark of Dravo Lime Co.

a. Name of Vendor: Environmental Technology Corporation
Suite 200
1517 Woodruff Street
Pittsburgh, PA 15220

Contact: Albert R. Kupsiec, Vice President
(412) 431-8586

b. Category of fixing process: The ETC Solidification System requires commonly available reagents in addition to the lime which is currently used in wastewater processes. The hazardous wastes are neutralized and solidified resulting in a sludge which totally encapsulates the moisture and chemically binds heavy metals and other chemicals within the sludge.

Lime is required to neutralize the acidity of the hazardous waste and to complex most of the heavy metal cations as insoluble hydroxides. Chemistry of the reagents is well known, but before now they had not been used in a single system. One of the reagent acts as an ion exchange media for complete heavy metal removal and removes excess water within the system. The other reagents act as binders which bridge the sludge particles and increases the physical strength and load-bearing capacity of the final sludge. The final sludge produced is soil-like in appearance.

c. Types of waste treated: The hazardous wastes involved in the development of the ETC system are mostly spent pickling acids from steel mills. Sulphuric acid composes the largest amount of wastes by volume. Other types of wastes treated include (1) hydrochloric acids; (2) other pickling acids; (3) spent plating solutions; (4) sludge from industrial waste treatment plants; (5) scrubber sludges; and (6) organic sludges.

d. Types of waste excluded from treatment: None listed.

e. Approximate cost of processing: Cost of neutralizing and solidification of waste pickle liquors varies with the method of mixing and type of lime used. Treatment with dry lime followed by ETC reagents costs one cent per liter. Addition of lime as a slurry increases the amount of the other reagents required so that the costs rise. Other sludges can be stabilized at costs of 0.40 cents to 3.00 cents per liter.

f. Data on leach and strength tests: Leach tests were conducted in the open in lined, V-shaped trenches fixed with perforated plastic pipe which directed all leached liquid into plastic collection buckets. After about one month the leachate from 10 different sludges had from 1000-5000 mg/l total dissolved solids, 500-800 mg/l $SO_4$ and 150-600 mg/l Cl. Analysis for heavy metals showed less than 0.01 mg/l of nickel, zinc, iron, chromium and manganese. Only copper was present at 0.03-0.04 mg/l levels. Hardness (i.e. physical strength) is a function of the total amount of solids present and the quantity of reagents added.

g. Examples of past applications and current contracts: None reported.

a. Name of Vendor: Envirotech
3000 Sand Hill Road
Menlo Park, CA 94205

Contact: David L. Keaton, Vice-President

NOTE: For information on treatment of $SO_2$ sludges contact:
Walter Renburg, Jr.
Air Group/Pittsburgh
Envirotech Corporation
Two Airport Office Park
400 Rouser Road
Pittsburgh, PA 15108

b. Category of fixing process: The process is sodium silicate and cement-based. (U. S. Patent 3,837,872) Envirotech is the exclusive licensee in the field of fixed treatment units for National Environmental Control, Inc. (parent company of Chemfix Corporation).

c. Types of waste treated: Details available from company.

d. Types of waste excluded from treatment: Details available from company.

e. Approximate costs of processing: Figures available from company.

f. Data on leach and strength tests: Can be obtained from company.

g. Examples of past applications and current contracts: Contact company directly.

a. Name of Vendor: I. U. Conversion Systems, Inc.
115 Gibraltar Road
Horsham, PA 19044

Contact: Norman F. O'Leary, Vice President, Marketing; or
Richard W. Patton, Industrial Sales Manager
(215) 441-5920

b. Category of fixing process. The IUCS Poz-O-Tec process utilizes fly ash and other additives. The Poz-O-Tec chemistry is a combination of two simultaneous reactions: a rapid reaction that occurs between the soluble salts present in fly ash and the lime and alumina that is found in the fly ash glass; and a slower pozzolanic reaction that occurs between the silica in the fly ash and lime. The latter reaction occurs over a period of months.

c. Types of waste treated: This solidification system was developed initially for the electric utility industry for $SO_2$ scrubber sludge stabilization. Four million tons of FGC sludge is treated by this process in a single year.

Conversion Systems has also successfully stabilized and tested electroplating wastes, steel mill wastes, and chemical process wastes. Based upon these results, the process can stabilize or encapsulate wastes having the potential of leaching salts or heavy metals into the environment.

d. Wastes not suitable for treatment: Some organic wastes.

e. Approximate cost of fixation: Each waste must be evaluated for each client by Conversion Systems. Several alternative methods are available which result in somewhat different scopes of service. Preliminary cost estimates for processing sludges usually fall in the range of 1 to 7 cents per liter of waste. Some parameters influencing this range are quantity to be processed, water content, waste toxicity, equipment redundancy, desired methods of operation and scheduling requirements.

f. Leach and strength tests: Physical and environmental properties of Poz-O-Tec improve with time as the pozzolanic reactions proceed. The cementitious reaction produces a monolithic mass of low permeability which is subject to surface leaching only. The following is a compilation of typical structural properties of Poz-O-Tec stabilized material:

| | |
|---|---|
| Wet density | 1360-1600 $kg/m^3$ (85-100 lb/cu ft) |
| Dry density | 1040-1360 $kg/m^3$ (6585 lb/cu ft) |
| Moisture content | 2550% moisture |
| Cohesion | >95.7 x $10^3 N/m^2$ (>2000 lb/sq ft) |
| Unconfined compressive strength | >1.2 x $10^3 N/m^2$ (>25 lb/sq ft) |
| Permeability coefficient | $10^{-6}$ to $10^{-8}$ cm/sec |
| Allowable bearing capacity | 2.87 x $10^5 N/m^2$ (3 tons/sq ft) |
| Stable fill slope | 2 horizontal to 1 vertical |
| Saturation | incomplete |

Poz-O-Tec stabilized sludge may occupy more volume than the unstabilized sludge, but any increase in material is offset by the weight reduction brought about by dewatering the sludge before treatment and the greater heights to which the fixed sludge pile can be built in the disposal area.

g. Examples of past applications and current contracts: Conversion systems currently has contracted to fix 8 million metric tons of $SO_2$ scrubber sludge produced at eleven electric power plants in the U. S. It is also stabilizing all wastes from an $SO_2$ scrubber and water treatment plant of a large battery manufacturer.

The company is also developing alternative disposal applications where the physical characteristics of the fixed sludge can be used to advantage. Poz-O-Tec stabilized materials have been used as a base in parking lot and road beds. Cast Poz-O-Tec blocks are currently under study for use in constructing artificial reefs.

Poz-O-Tec is a registered trademark of I. U. Conversion Systems, Inc.

a. Name of Vendor: Industrial Waste Management, Inc.
Suite 70, 340 E. 64th Street
New York, New York 10021

Contact: B. Alva Schoomer, President
(212) 355-1979

b. Category of fixing process: The Enviroclean process may utilize portland cements or lime and pozzolaus or cement and lime and pozzolans depending upon desired results and local availability in some instances. Processed waste is soil-like in consistency and becomes concrete-like mass. Strength continues to develop over period of years. U.S. patent pending on process. Company emphasis is on recycling of wastes by processing right on site into roadways, parking lots and walkways.

c. Types waste treated: Industrial, utility and certain municipal wastes.

d. Wastes not suitable for treatment: Most organics and wastes of less than 15% solids for reasons of economics.

e. Approximate cost of fixation: \$12/yd$^3$ to \$20/yd$^3$ (\$15.60 to \$26.20/m$^3$) not including removal, hauling or final disposal. Cost will vary with individual sludge chemical composition, water content and volume to be processed.

f. Leach and strength tests: Both leach test results and strength development as well as permeability will vary by the chemical addition rate and the type of sludge. Initial strengths in the 15 to 40 lbs/ft$^2$ range develop 75 to 400 lbs/ft$^2$ range in 3 to 6 months typically and 300 to 700 lbs/ft$^2$ in two years. Permeabilities initially in the $10^{-5}$ to $10^{-6}$ cm/sec range will reduce to $10^{-7}$ to $10^{-8}$ within one month. A 48 hr. leachate test with distilled water from a toxic metal hydroxide sludge from an etching operation report ion concentrations below 0.5 ppm for Cu, Fe, Pb, Zn, Cr (total), $PO_4$, Ni and Cd.

Volume increase from addition of materials for chemical stabilization will vary from 1.1 to 1.6 times pretreatment volume.

g. Examples of past application and current contracts: Company is currently entering U.S. market. Past applications available directly from company. Enviroclean is a pending service mark of Industrial Waste Management, Inc.

a. Name of Vendor: Newport News Industrial Corp.
230 41st Street
Newport News, VA 23607

Contact: J. R. May, Manager, Radwaste Management Systems
(804) 380-7761

Newport News Industrial Corporation is primarily involved with volume reduction and waste handling techniques for radioactive materials. They have broad experience with producing compact wastes that are compatible with solidifying agents such as urea-formaldehyde, water extendable polyesters and bitumen. They are currently in the process of developing a new solidification method applicable to hazardous chemical wastes including radwastes.

b. Category of fixing process: Not available.

c. Type of waste treated: Not available.

d. Type of waste excluded from treatment: Not available.

e. Approximate cost of processing: Not available.

f. Data on leach and strength tests: Not available.

g. Examples of past application and current contacts: Process still in developmental stage.

a. Name of Vendor: Canadian Waste Technology, Inc.
160 Torbay Road
Markham, Ontario L3R-1G6
Canada
Contact: David Krofchak, President, Canadian Waste Technology, Inc.
(416) 495-9502

b. Category of fixing process: The solidification process is based upon the production of stable silicate compounds analogous to natural geologic materials.

c. Type of waste treated: All inorganic wastes from heavy, medium and light industries such as waste pickle liquor, plating wastes, etc., containing acids, chromium, copper, iron, magnesium, manganese, nickel, zinc, cadmium, lead, mercury, vanadium, chlordies, sulphates, phosphorous and virtually any inorganic chemical or combination thereof. Specialized applications have been designed to treat mine tailing wastes and sewage sludges from primary and secondary treatment plants.

d. Types of waste excluded from treatment: The process is ineffective against some organic wastes, but organic wastes of up to 20% of the volume of the formulated inorganic wastes have been treated successfully on a case to case basis.

e. Approximate cost of processing: Each location where wastes are treated has different costs depending upon quantity of wastes and the method of operation. However, costs of approximately $8.00 per cubic meter ($6.00 per cubic yard) or 0.8 cents per liter (3 cents per gallon) are easily achieved (August 1977). This price assumes no cost for removal of solidified material from the site. No apparent increase in fixed material to raw sludge volume has been found.

f. Data on leach and strength tests: Extensive strength and leach tests have been made by the company; those cited below were in cooperation with the Ontario, Canada, Ministry of the Environment, Pollution Control Branch, Industrial Section (from a paper entitled "An Assessment of a Process for the Solidification and Stabilization of Liquid Industrial Wastes, 1976, by G. A. Kerr, Q.C., Minister) the conclusions of this report were:

(1) The solidification process appeared to hold and stabilize most of the heavy metals contained in the liquid (acidic metal-bearing liquid industrial wastes). Heavy metal values in the leachates (laboratory and field) were commonly below 1 mg/liter.

(2) Leachates from the testing of processed material contained high concentrations of dissolved solids.

(3) The bulk of the common heavy metals present in the waste were retained in the processed material during extended period of leaching with distilled water when considered on a mass basis. Losses of heavy metals were relatively minor.

(4) Landfilling may be used to dispose of the processed material providing adequate facilities are available for the collection and treatment of leachate and run-off. The concern over dissolved solids contamination will dictate the adequacy of the facilities required.

Material with up to 20.7 x $10^6$ N/$m^2$ (3000 psi) unconfined compressive strength has been produced, but for reasons of cost, the end product is generally of low strength.

g. Examples of past applications and current contracts: Currently over 380,000 liters/day (100,000 gpd) are being treated at a treatment site in the city of Hamilton, Ontario. The fixed material is being used as a cover for the sanitary landfill. Negotiations are currently underway with companies in the United States and in Canada for the licensing of the technology to operate similar sites and many cases to treat company wastes on site.

a. Name of Vendor: Polymeric Materials Section
Department of Materials Science and Engineering
Washington State University
Pullman, WA 99164

Contact: R. V. Subramanian
(509) 335-6784

NOTE: The Department of Materials Science and Engineering, Polymeric Materials Section is not a vendor of the raw materials and equipment necessary for fixation, but has extensive experience and developmental expertise in the polyester encapsulation of hazardous wastes. In cooperation with members of the Department of Chemical Engineering, this technology has successfully been developed through the pilot plant stage.

b. Category of fixing process: An organic polymer (polyester resin) is used to solidify the wastes.

c. Types of waste treated: Although very broadly effective, the process appears to be quite effective for low-level radioactive wastes, metal ion wastes, cyanides, arsenic wastes, and some specific organic wastes such as kepone, PCB, and some pharmaceuticals.

d. Type of waste excluded from treatment: The process is not effective on very highly acidic sludges (especially at pH less than 1.0).

e. Approximate cost of processing: The price of polyester resin is about $1.00/kg (45 cents/lb). Since the maximum volume fraction of close-packed spheres is 74%, the minimum amount of resin which must be added to the waste is about 25% by volume. The fixed waste is usually 133% to 175% of the volume of the unfixed waste.

f. Data on leach and strength tests: Tests made using a fixed product encapsulating 60% by weight of a 24% sodium sulfate solution indicated compressive strength of $15.0 \times 10^6$ N/m$^2$ (2180 psi). Irradiation with 600 Mrad gamma radiation actually increased the compressive strength to $20.7 \times 10^6$ N/m$^2$ (3000 psi). The strength of the product is dependent upon the type, proportion and form of waste incorporated.

The leachabilities of Co-58, Sr-85 and Cs-134 from a similar encapsulated sodium sulfate waste were $3.2 \times 10^{-3}$, $3.5 \times 10^{-3}$, and $5.9 \times 10^{-3}$ cm, respectively over a period of 120 days. The leach curves leveled off at this value after an initial rise in the first 20 days. Thus, the leachability, after the initial dissolution of surface material, was practically negligible.

g. Examples of past applications and current contracts: Ontario Hydro, Toronto, Ontario is pursuing this process for rad waste encapsulation.

a. Name of Vendor: Protective Packaging, Inc. (NECO)
A Subsidiary of Teledyne Corp.
328 Production Court
Jeffersontown, KY 40299

Contact: Charles Jay
(502) 491-8300

b. Category of fixing process: The company sells an organic polymer solidification system.

c. Types of waste treated: Company has extensive experience with nuclear wastes, both in solidification and disposal. Details are available from the company.

d. Types of waste excluded from treatment: Consult company directly.

e. Cost of fixation: Information available from company.

f. Leach and strength test: Details on testing with radwastes available.

g. Examples of past applications and current contracts: Available directly from company.

a. Name of Vendor: Sandia Laboratories
Albuquerque, NM 87115

Contact: R. L. Schwoebel, Manager
Chemistry and Materials Characterization Department
(505) 264-4309, ext. 5820

NOTE: Sandia's waste management program is wholly oriented toward stabilization of radiation containing wastes (July 1975).

b. Category of fixing process: The Sandia Solidification Process project is a feasibility study of the solidification of solid wastes. Fission products cations and actinides undergo ion exchange on inorganic ion exchangers being developed at Sandia Laboratories. These ion exchangers are hydrous oxides of Ti, Zr, Nb, Ta.

c. Type of waste treated: The process is designed for high-level radioactive wastes such as the high level waste stream resulting from commercial nuclear fuel reprocessing was well as caustic defense waste streams with high salt ($NaNO_3$) contents.

d. Type of waste excluded from treatment: The high cost of process precludes low value, low hazard wastes.

e. Approximate cost of processing: Cost estimates for continuous column flow systems are comparable to glassification processes. Periodic batch processing would probably be cheaper than glassification.

f. Data on leach and strength tests: The final product, subsequent to ion exchange, could be fired to produce a ceramic product (mixed titanates and titania) having leach rates as much as an order of magnitude lower than that of borosilicate glass stabilized waste.

g. Examples of past applications and current contracts: Process in feasibility study stage only.

a. Name of Vendor: Sludge Fixation Technology, Inc.
227 Thorn Avenue
P. O. Box 32
Orchard Park, NY 14127

Contact: Richard E. Valiga
(716) 662-1005

b. Category of fixing process: The Terra Crete process is a "self-cementing process" based on the production of a cementitious material from calcium sulfite hemihydrate or calcium sulfate. A portion of the sulfite/sulfate sludge stream is dried and calcined to produce a cementitious agent. This material and other additives (as needed) are introduced into the waste stream and react to form a hard, low permeability mass from the sludge.

c. Types of waste treated: The system is primarily designed to operate with sulfite/sulfate-based sludges produced from $SO_2$ stack scrubbing operations but is adaptable to other situations where calcium sulfite/sulfate sludges can be obtained.

d. Types of wastes excluded from treatment: Not specified.

e. Cost of fixation: A flue gas cleaning sludge would cost between $2.00 -2.75 per ton for fixation.

f. Leach and strength tests: Data on leaching of antimony and lead-rich flue gas cleaning sludge shows 0.01 ppm lead in the leach liquid. The unconfined compressive strength obtained from the Terra Crete material depends on the amounts of additive used, but data showing strengths from $9.57 \times 10^4$ $N/m^2$ (200 $lbs/ft^2$) to $5.74 \times 10^5$ $N/m^2$ (12,000 $lbs/ft^2$) are available. Permeabilities are on the order of $10^{-6}$ to $10^{-7}$ cm/sec.

g. Examples of past applications and current contacts: None specified.

Terra Crete is a registered trademark of Sludge Fixation Technology, Inc.

a. Name of Vendor: Southwest Research Institute
8500 Culebra Road
P. O. Drawer 28510
San Antonio, Texas 78284

Contact: John M. Dole, Manager
Process Research & Engineering

NOTE: Southwest Research Institute (SRI) is a contract research organization and as such is not marketing processes or products.

b. Category of fixation process: Two fixation processes have been developed:

(1) SRI has developed a thermoplastic epoxy system that combines the better features of thermosetting epoxy system with the better features of thermoplastic systems. Low-cost extended epoxy resins and hardeners which are solids at ambient temperatures are heated (204°C) where they become low viscosity liquids. They are then combined and mixed with heated fillers or aggregates and discharged. They set instantly as thermoplastic materials and then cure as a thermosetting material to provide the typical physical property features of epoxy containers. These epoxy materials can be used as coatings for other fixation processes.

(2) Three different systems using sulfur have been developed for industrial sludge stabilization. These systems are: (a) a modified sulfur process where sulfur is used as a binder for the toxic sludge to produce a concrete-like material. Since sulfur melts at about 120°C, the sludge must be heated and dried before processing. Because of the brittle nature of sulfur, a modified form is usually found to be superior for concrete applications; (b) the plasticized liquid sulfur system is a new development in which sulfur is modified to the extent that it can be used as a substitute for asphalt; (c) the third process is sulfur impregnation. Surfur has been used previously as an impregnation agent for concrete, gypsum, porous brick, tile and mud block. In addition to filling the voids to reduce water absorption, considerable strength improvements also result. This system is of use in increasing the strength and leach resistance of sludge fixed by other methods such as concrete admixing. Most of the sulfur composite work listed above is still in the developmental stage.

c. Types of wastes treated: Not fully determined.

d. Wastes not suitable for treatment: Not fully determined.

e. Approximate cost of fixation: Not determined.

f. Leach and strength tests: Not yet available.

g. Examples of past applications and current contracts: Currently in development and testing phase.

a. Name of Vendor: Stabatrol Corporation
1402 Conshohocken Road
Norristown, PA 19401

Contact: Richard E. Valiga
(215) 279-3992

b. Category of fixing process: The Terra Tite process involves the addition of cementitious materials to the waste sludge to produce a concrete-like material.

c. Types of waste treated: Most industrial wastes can be treated. The Terra Tite process has great technical flexibility.

d. Types of wastes excluded from treatment: None specified.

e. Cost of fixation: None specified.

f. Leach and strength tests: Permeabilities on the order of $10^{-7}$ cm/sec are obtained. Leaching is insignificantly low. Terra Tite material has shown unconfined compressive strengths up to $4.78 \times 10^5$ N/$m^2$ (5 tons/sq ft).

g. Examples of past applications and current contacts: Heavy metal sludges, 50,000 tons; heavy metal salt cake, 10,000 tons; contaminated soils, 5,000 tons.

Terra Tite is a trademark of Stabatrol Corporation.

a. Name of Vendor: Stablex Corporation
Suite 112
2 Radnor Corporation Center
Radnor, PA 19087

Contact: John Scofield
(215) 688-3131

b. Category of fixing process: The patented technology, described as Sealosafe, involves adding two silicate-based powders to the waste which is dissolved or dispersed in water thereby producing a slurry and the slurry sets into a rigid, rock-like cast. Due to its physical and chemical form, this mass is referred to as synthetic rock.

The physical and chemical interactions which take place simultaneously are referred to as the mechanism of crystal capture. Up to ten additional ingredients are also used, depending upon the type of waste to be treated, to enable the crystal capture mechanism to operate under optimum conditions.

c. Types of wastes treated: The process is suitable for:

(1) All inorganic wastes.

(2) Organic wastes which can be homogenously incorporated into an aqueous phase either by dissolution, suspension, or absorption.

(3) Wastes in (1) or (2) above in liquid, solid, or sludge form, including contaminated articles such as filter cartridges, clothing, rubber boots, etc.

(4) The process is exceptionally successful in treating all heavy metals, arsenic, mercury and asbestos. The process also deals with anionic wastes such as fluoride, chloride, etc.

d. Wastes not suitable for treatment: The process is not suitable for solidification of:

(1) Oils, solvents, and greases which are not miscible with an aqueous phase.

(2) Very large quantities of water with minimal amounts of toxic ingredients.

e. Approximate cost of fixation: In typical applications one ton of waste would yield 1.15 to 1.4 tons of end product, called Stablex. The volume increase in this weight increase is between 5% and 10%.

Precise cost estimates are not possible because of the different properties of the wastes to be treated. Experience indicates an extremely broad range of between $5.00 to $350.00 per ton depending upon the type, quantity and complexity of the waste involved.

f. Leach and strength tests: Extensive experience and information is provided by the company. The product, Stablex, is 10 times less permeable than concrete. Leaching tests in which fixed samples are ground to a fine powder and totally immersed and wetted in ten-times their weight of distilled water for one hour indicate that very little material is lost to the water. One example using a solid waste fixed by the process and hardened for three days (and containing 39,000 ppm copper, 46,000 ppm zinc, and 42,000 ppm chromium) lost less than one ppm of these toxicants. The product, Stablex, has an unconfined compressive strength about equal to that of the grouts used for void filling and soil stabilization but much lower than concretes and mortars.

g. Examples of past applications and current contracts: A treatment center near Birmingham in the United Kingdom has a current throughput of 200,000 tons of waste per year (its capacity will be increased from 70,000 tons per year in 1978). Another treatment center near London, U.K., was commissioned in 1978 with a capacity of 400,000 tons per year. Both plants operate as regional treatment plants handling a variety of wastes from different sources. Construction of two plants in Japan and the first plant in the U. S. has been scheduled to begin in 1979.

The Sealosafe Service includes a process protected by patents and patent applications in the United States and overseas and Sealosafe and Stablex are trademarks of the Stablex Group of Companies.

a. Name of Vendor: TJK, Inc.
7407 Fulton Avenue
North Hollywood, CA 91605

Contact: Masaaki Endo, General Manager
(213) 875-0410

NOTE: This company has contracted to market the Takenaka Sludge Treatment (TST) System (Takenaka Komuten Co., Osaka, Japan) in the U. S. Studies conducted by EPA on Kepone and arsenic disposal problems are now underway.

b. Category of fixing process: Hardeners are principally cement-family or cement-based materials. In addition, special additives are used for stabilizing harmful substances. Several series of hardeners are used depending upon the specific mud or sludge to be treated.

c. Type of waste treated: The TST system is a technique for solidifying mud of comparatively high water content or sludge discharged from factories and plants. It transforms the material into a form easy to handle for utilization in land reclamation and pollutant control. Treatable material can be widely dispersed, settled sludge or sludge obtained directly from the factory or plant. In the case of sludges with toxic substances such as mercury, chromium and cadmium, TST treatment stabilizes and chemically fixes these harmful substances.

d. Types of waste excluded from treatment: Two types of sludges tested but found unsuitable are sludge produced from a wool scouring plant (greater than 20% fats and oils) and sludges containing large amounts of paints wastes.

e. Approximate cost of processing: Costs of processing will, of course, vary with the type of sludge and additives required but will run from about $\$10/\mathrm{m}^3$ ($\$8/\mathrm{yd}^3$) to $\$20/\mathrm{m}^3$ ($\$16/\mathrm{yd}^3$). These estimates do not include transportation or disposal. Volume increase upon treatment is from 1.05 to 1.15 times pretreatment volume.

f. Data on leach and strength tests: Extensive leach testing has been carried out by the company. In their standard leach test, the treated sludge is ground to a particle size between 0.5 mm and 5 mm. This powder is then mixed with distilled water and adjusted to pH of between 5.8 and 6.3 with HCl or $CO_2$. The final mixture (100 ml) is 10% (weight/volume) sludge to water. This mixture is stirred for 6 hours at room temperature and 1 atmosphere and then filtered or centrifuged before analysis. Results of tests made with a wide variety of sludges and muds containing a wide variety of toxic metal ions show that only low levels of pollutants are released even in this relatively severe leaching test. (Ions reported and their maximum allowable concentrations: Alkyl-Hg and Hg, no detectable; Cd, 0.3 mg/l; Pb, 3 mg/l; organic-P, 1 mg/l; $Cr^{+6}$, 1.5 mg/l; As, 1.5 mg/l and CN, 1 mg/l.)

Unconfined compressive strength varies widely with the type of sludge and kind and amount of additives used, but values of 5-10 x $10^5$ $N/m^2$ are not unusual with 20% (w/v) additives.

g. Examples of past applications and current contracts: Twenty-six projects have been completed since 1973. Seventeen projects involved deposits under water (46,000 $m^3$), seven involved factory discharges (14,500 $m^3$). In the majority of these projects toxic substances were successfully contained.

a. Name of Vendor: Todd Shipyards Corporation
Research and Technical Division
P. O. Box 1600
Galveston, Texas 77553

Contact: C. E. Winters, Jr., Sales/Marketing Representative
(800) 2312868/2869 (713) 744-7141

b. Category of fixing process: The organic polymer product called "Safe-T-Set", is a non-toxic, non-hazardous, powdered, thixotropic thickner which is effective with concentrated wastes as well as liquids. Safe-T-Set solidifies into a homogenous mix with no liquid displacement. It is not a urea-formaldehyde formulation.

c. Types of waste treated: This product was designed specifically for industrial radioactive waste sludges. Tests have not been made with general industrial wastes at this time (Dec 1978).

d. Type of waste excluded from treatment: No extensive tests have been made.

e. Approximate cost of processing: Costs will vary with the amount of additive used to solidify the mass. Typical data given by the company indicate that 6 to 20% Safe-T-Set are typical and give hardening time of 14 to 3 minutes respectively at 21°C. The cost of Safe-T-Set is approximately $6.60/kg in 500 kg quantities (4/77). Additive costs (at 10%) would be approximately $600 per ton of fixed waste.

f. Data on leach and strength tests supplied by the company: Extensive leaching and strength tests are reported by the company. These tests were conducted with simulated radioactive wastes and were designed to prove that Safe-T-Set, when mixed with radioactive liquid waste, would minimize activity release if container integrity was lost during transportation or after disposal by burial. Nine tests were performed: Escape of radioactive material through Safe-T-Set and soil, temperature cycle test, immersion study of pH dependance, pH of fixation, immersion study at pH 7.0, off gas study, stability when innoculated with bacteria, irradiation and toxicity.

g. Examples of past applications and current contracts: No information available.

Safe-T-Set is a trademark of Todd Shipyards Corp.

a. Name of Vendor: TRW Systems Group
One Space Park
Redondo Beach, CA 90278

Contact: H. R. Lubowitz, Staff Scientist
(213) 535-4321

NOTE; TRW Company has done extensive testing, development and evaluation on fixation technology for the EPA. Data below was taken from Recommended Methods of Reduction, Neutralization Recovery or Disposal of Hazardous Waste by Burk, Derham, and Lubowitz of TRW, USEPA contract #68-03-0089, 21 June 1974, and Lubowitz and others, 1977, Development of a Polymeric Cementing and Encapsulating Process for Managing Hazardous Wastes, EPA-600/2-77-045.

b. Category of fixing process: The two types of fixation additives which were selected for best overall potential and then studied and tested extensively were:

(1) Inorganic cements: Type 2 Portland cement, plaster of paris (calcium sulfate hemihydrate) and lime (pure calcium oxide).

(2) Polybutadiene resins of specific stereo configurations (atactic 1, 2-polybutadiene).

All fixation techniques were tested with and without jackets of both thermoplastic and thermosetting resins and asphalt.

c. Types of waste treated: All types of solid wastes and sludges were felt to be treatable, but the specific wastes treated in this study were simulated solid wastes and sludges containing compounds of six toxic elements: arsenic, mercury, selenium, chromium, cadmium, and lead.

d. Wastes not suitable for treatment: None given.

e. Approximate cost or processing: Process design and economics were covered extensively in the study. Details of the design and economics of both the organic and inorganic encapsulation processes, cost benefit analysis and a summary of results were included. Raw material cost was the factor most affecting the process costs and was a primary consideration in the original selection of the fixation processes.

f. Data on leach and strength tests: Extensive tests were made and results are available. Tests made included: mechanical testing, determination of bulk density, surface hardness, and compressive strength; microscopic examination of the interface between fixed specimen and the coating and leaching experiments using three leaching solutions (distilled water, saturated carbonic acid of pH 3.8 to 4.0, and 0.1M sodium sesquicarbonate solution). Leaching was conducted at room temperature in 750 ml of leaching solution which was mildly agitated twice per day.

g. Examples of past applications and current contracts: Not available.

a. Name of Vendor: Werner and Pfleiderer Corp.
160 Hopper Ave.
Waldwick, NJ 07463

Contact: John Stewart or Richard Doyle
(201) 6528600

NOTE: Werner and Pfleiderer Corporation manufactures equipment for incorporating low and intermediate level radwastes into a bitumen or plastic matrix. Their equipment and their techniques have been used in almost all testing of bitumen encapsulation of hazardous industrial wastes.

b. Category of fixing process: The technique used is bitumen encapsulation or incorporation using a screw extruder.

c. Types of wastes treated: No industrial wastes are currently being stabilized by asphalt encapsulation but, testing of asphalt encapsulated arsenical wastes has been undertaken by the U. S. Environmental Protection Agency.

d. Types of wastes excluded from treatment: Sludges containing strong oxidizers such as nitrates, chlorates, perchlorates and persulfates should not be encapsulated in asphalt. Sludge containing borates may require special handling because they tend to cause early hardening of asphalt materials. Salts that swell excessively on rehydration may require special processing.

e. Cost: Not available for industrial wastes at this time. Usually wastes are mixed on 1-to-1 weight ratio asphalt to dry wastes. Asphalt of suitable grade for blending cost 13 to 35 cents per kg. Capital, operating expenses are presently not available for non-radioactive disposal operations. The cost of secondary containers (55-gallon steel drums) must also be added in.

f. Leach and strength tests: According to information furnished by the company, leach rates 100 times less than those observed with comparable cement mix can be expected. If the microdispersed salt/asphalt mix is coated with as little as 5 mm (0.2 in.) of pure asphalt the leach rate was zero in distilled water over a period of two and one-half years. Strength test data are not obtained for asphaltic mixes as there are plastic solids that are usually placed in steel containers.

g. Examples of past applications and current contracts: Full scale radwaste encapsulation units are in operation at Marcoule, France and Karlsruhe, West Germany. No one is presently using similar equipment in industrial waste processing.

# APPENDIX B

# PROPOSED UNIFORM LEACH PROCEDURE

## B.1 BACKGROUND

The leachability of a solidified waste can be considered to be a physical property of the material much like specific gravity or unconfined compressive strength. As such, the leaching characteristics of the solid can be measured to a high degree of accuracy using uniform or "standard" leaching procedures. Uniform methodology is needed because leachability is specific for the species being leached, the composition and rate of flow (or replacement time) of the leaching medium, and other details of the leaching vessel and procedure. The procedure proposed is analogous to those used to determine other physical and/or chemical properties in that environmental and long-term factors which might effect the property are not taken into account.

Consideration of the leaching characteristics of a solidified waste material is also best separated from any environmental factors which might be encountered at the disposal site, and from the attributes of any packaging or jacketing material. For most purposes, the single most important characteristic of the waste solid itself is the rate at which it will lose constituents to the environment, and particularly, to contacting waters--i.e. its leachability. For this reason, a wide array of "standard" leach tests have been derived for specific waste products and/or conditions which have little commonality or theoretical basis. Comparison of results from different leach testing procedures is difficult or impossible.

The Uniform Leach Procedure (ULP) presented here is proposed as a practical, reproducible, and rapid test which will provide data that can be used to compare directly the leaching characteristics, different solidified waste products, and/or to give a quantification of the leaching property of different production runs of the same treatment process for quality assurance. It is not proposed to assess parameters which might be significant at specific waste disposal sites or for single samples of individual waste solidication/stabilization processes. No attempt is made to mimic the actual conditions that the waste might encounter upon shallow burial or other disposal activity. No accelerating conditions, such as caustic leaching media or elevated temperatures are used. The ULP is designed only to give a quantitiatve and comparable measure of the waste solid's leachability. It is similar in conception, practice, and interpreation to the International Atomic Energy Agency standard leach test proposed originally in 1971(C-4) and to its subsequent modifications, such as the "Standard on

Leachability of Solidified Radioactive Waste" being developed by the American Nuclear Society Working Group ANS-16.1 (O. U. Anders, personal communication).

The long-term leaching rate is strongly influenced by many factors such as the occurrence of chemical reactions between the leaching fluid constituents (such as dissolved $CO_2$ or oxygen) and the surface of the solid, changes in the leachate pH and erosion, corrosion, or product spalling or cracking. These factors which present the greatest difficulty to the prediction of the long-term stability of the treated waste product cannot be approached by short-term leaching tests and require long-term, site-specific laboratory or field studies to determine. For specific situations, the ULP can be run in conjunction with leaching tests which incorporate site or process specific parameters such as leaching medium composition, temperature changes, time and numbers of elutions, ratio of leaching medium volume to weight of waste, etc. Results of these site-specific, specialized leach tests, when compared to the uniform test results, will serve to estimate the degree to which the particular disposal conditions will affect the release of contaminants from the treated wastes--i.e. their leachability. Such leach procedure results, thus "calibrated", can be used to monitor the continued effectiveness of the treatment process or variations of it, over the permit period.

The products of all common solidification/stabilization processes can be evaluated using the Uniform Leach Procedure. Wastes treated with cement, lime or flyash, asphalt or other organic binders such as urea-formaldehyde resin and other plastics, or glass and ceramic materials and their composites can be evaluated using the ULP and the results compared directly with each other.

## B.2 THEORETICAL BASIS OF THE UNIFORM LEACH PROCEDURE

Several mechanisms which are responsible for the loss of constituents from solid masses have been identified and described in various studies of leaching behavior of solid materials (B-1 to B-7). An early effect in any leach test is an initial "wash-off" of small particulates adhering to the surface of the test speciman in which the concentrations of most potential contaminants are usually very high. After this phase, the concentration of contaminant species in the leachate is determined either by their maximum solubility in the leaching medium or by their rate of diffusion to the surface of the solid where solution can take place. The ULP incorporates both an initial rinse or "wash-off" and a relatively short-term (14 day) static leaching test. Results are evaluated using solution or diffusion kinetic theory.

The initial "wash-off" portion of the test produces a measure of the amount of material on the surface of the solidified material which is not incorporated into the solid matrix and is thus immediately available to the leaching medium. This aspect of the leaching of treated waste products is ignored altogether in most test procedures or simply lumped together with the initial leachate samples. However, it represents a serious problem to the interpretation of the leaching test results. The "wash-off" material is also a separate problem from the longer term loss of contaminants. The amount of "wash off" material often can be modified directly by attention to mold design or curing techniques. Solidified products which have extremely high "wash-off" contaminant levels may be refused or rejected on this ground alone. The ULP allows airblasting of the product surface prior to testing, these high initial values must represent a highly mobile surface deposit. An initial leach rate which is lower than can be explained by diffusion or solution theory may be due to factors such as a delay in filling of any surface voids in the specimen or the presence of a surface film or other passive surface phenomenon which delays surface "wetting" or interaction of the surface with the leaching medium.

Solubility limited constituents in the leachate samples typically follow a pattern in which their concentration remains relatively constant at or near the maximum solubility of the constituent in the leaching solution. In this case, the amount of the constituent available to the leaching solution at the surface of the solid is greater, or is replaced more rapidly, than it is removed by solution in the leaching medium. Solubility limited leach rates or leaching kinetics are often found for major constituents in the waste or matrix material. Such is the case for calcium and sulfate ions in flue gas cleaning sludges or in many high sulfate industrial sludges which are neutralized with lime. Constituents present in low concentration in the waste but which have low solubility can also exhibit solubility limited leaching kinetics. For example, many heavy metals have constant leach rates in leaching tests made with alkaline, treated or untreated, industrial sludges (B-6). Minor variations in the pH, temperature, or presence of other competing ions in the leaching medium can cause rapid and erratic concentration changes of solubility limited leachate constituents by causing major changes in the solubility of the leaching species. Depletion of the low solubility constituents from the surface of the solidified waste will cause a change to internal diffusion-limited kinetics.

Those constituents which have solubility in the leaching medium higher than their availability for solution at the surface of the solid matrix show leaching kinetics which are described by classical diffusion theory--the rate of their appearance at, and solution from, the surface being dependent upon the rate of their diffusion from inside the matrix of the solidified waste to the surface. These internal diffusion-limited leachate constituents have high initial concentrations which decrease over time due to the depletion of the constituent in the surface layers of the solid matrix.

Solution of the mass transport equations for diffusion of a constituent from a semi-infinite medium (the waste-containing solid) has been shown to give the following expression (B-2):

$$\frac{\Sigma A_n}{A_o} = \frac{2S}{V}\left(\frac{D_e}{\pi}\right)^{\frac{1}{2}}(t)^{\frac{1}{2}} \qquad (1)$$

where

$\Sigma A_n$ = total amount lost in (n) leaching periods, mg

$A_o$ = initial amount in specimen, mg

$t$ = lapsed time to (n) sample, sec

$S$ = exposed surface area, $cm^2$

$V$ = volume, $cm^3$

$D_e$ = effective diffusivity (or diffusion coefficient), $cm^2/sec$

Equation (1) upon rearrangement yields:

$$D_e = \frac{\pi}{4}\left(\frac{\Sigma A_n (V)}{(A_o)(S)}\right)^2 (t)^{-1} \qquad (2)$$

From which the effective diffusivity (or diffusion coefficient) can be calculated directly.

The effective diffusivity is a measure of the mobility of the constituent in question in the solid matrix and is proportional to the rate at which it will reach the leaching medium at the surface of the solid and thus be lost. The effective diffusivity is independent of position on the surface, but is dependent upon the leaching species and the temperature. It must therefore be determined individually for each component of interest in the waste. A plot of the accumulated fraction of the constituent leached at each sampling time versus the square root of the sampling time should give a straight line (Equation 1) if internal diffusion is the mechanism determining the leaching rate. Note that the slope of the line is $2(D_e/\pi)^{\frac{1}{2}}$ so that the diffusion coefficient can also be calculated directly from this slope.

A second form of the leaching model uses the incremental leach losses $(A_n/A_o)$ rather than the accumulated mass lost $(\Sigma A_n/A_o)$ and has the advantage that the data points are not coupled (subsequent points do not include all errors present in prior sampling). This equation has the form:

$$\frac{A_n}{A_o} = \left(\frac{S}{V}\right)\left(\frac{D_e}{\pi}\right)^{\frac{1}{2}} \left[\frac{\Delta t_n}{\left(t - \frac{(\Delta t_n)}{2}\right)^{\frac{1}{2}}}\right] \qquad (3)$$

where

$A_n$ = amount of constituent lost in leaching period (n), mg

$\Delta t_n$ = duration of (n) leachate renewal period, sec

$\Delta t - t_n/2$ = elapsed time at middle of (n)leachate renewal period, sec

Solving Equation (3) for the diffusion coefficient, $D_e$, yields:

$$D_e = \pi \left( \frac{(A_n)(V)}{(A_o)(S)} \right)^2 \left[ \frac{t - \left( \frac{\Delta t_n}{2} \right)}{(\Delta t_n)^2} \right] \qquad (4)$$

For specimens which have high initial "wash-off" levels of the leaching species, a correction for the initial amount can be made by either leaving that value out of the accumulated fraction leached or by using the relationship:

$$\frac{\Sigma A_n}{A_o} - \frac{A_w}{A_o} = \frac{2S}{V} \left( \frac{D_e}{\pi} \right)^{\frac{1}{2}} (t)^{\frac{1}{2}} \qquad (5)$$

Where $(A_w/A_o)$ is the fractional amount of the constituent lost in the initial rapid "wash-off" operation. Use of the incremental mass loss (Equations 3 and 4) will also alleviate problems with high or low initial losses.

The amount of the species of interest leached (referred to as $\Sigma A_n/A_o$ or $A_n/A_o$) is dependent upon both the shape and the size of the leaching specimen. To compare between leach tests using differently shaped and sized waste solids, the equations for the amount leached incorporate the specimen's surface to volume ratio (S/V). Thus, the values of surface area ($cm^2$) and volume ($cm^3$) must be known accurately so that meaningful comparisons of the data can be made.

## B.3 THE LEACH TEST PROCEDURE

The ULP intentionally prescribes a detailed protocol to be followed explicitly as to leaching medium composition, leachate renewal frequencies, and other test conditions such as temperature and pressure. The major purpose of the ULP is to determine the effective diffusivity of the solidified material as supplied for comparative or quality assurance purposes. Other testing conditions and leaching medium compositions may be required to more nearly represent anticipated conditions under which the specific waste may be disposed; but such tests are not part of the ULP as proposed here. The

ULP is designed to be accomplished as reproducibly, and as simply and quickly as possible.

## Specimen Preparation

The waste to be solidified should be thoroughly mixed to assure a representative sample is used and should undergo preparative treatment as close to that experienced by the actual treated waste product as possible. Core drilling of large waste forms may be used to prevent edge effects in the small molds or disparity in treatment techniques due to scaling effects. The solid specimen must have a defined and known size and shape (such as a monolithic cylinder, parallelepiped or sphere). Cylinders must have diameter-to-length ratios, and parallelpipeds a minimum thickness-to-length ratios, of from 0.2 to 5. A cylindrical shape is preferred. The minimum dimension in any direction is 1 cm. All details of solidification, casting, curing, and storage conditions and containers shall be reported.

The surface of the specimen must be smooth, without voids, and homogeneous so that the calculated surface area approximates the true surface exposed to the leaching medium. The surface should not be washed or wetted before testing but may be air blasted to remove lose particles and dust.

## Leaching Test Vessel

No specific vessel shape or dimensions are required, but the following points must be noted. The vessel must be nonreactive with respect to the leachate and the waste test specimen and must not adsorb species of interest during the leaching test. It must prevent excessive evaporation of leachate. The geometry of the vessel must allow all of the external surface of the specimen to be exposed to the leaching medium using the volume of leachate specified below and to have sufficient free space to allow handling of the leachate and the test specimen. Sufficient space must be available in the vessel so that the test specimen is surrounded on all sides by leaching medium at a depth equal to or greater than the smallest specimen dimension. A support for the test specimen to rest upon must be provided in the vessel; it must not interfere with leachate addition or removal, cause damage to the specimen, or cover more than 2% of the surface of the specimen.

## Leaching Medium

The leaching medium used in all Uniform Leach Procedures is demineralized water with an electrical conductivity of less than $10^{-5}$ mho/cm at 25°C and a total organic carbon content of less than 5 ppm. The leaching medium should be equilibrated with air so that it is saturated with respect to oxygen and carbon dioxide, and has a pH of between 4 and 5.5.

The volume of leaching medium used for each leaching interval shall be related to the surface area of the specimen by the following relationship:

$$\text{leaching medium } (cm^3)/\text{surface area } (cm^2) = 10.0$$

This ratio was selected as a compromise between having sufficient volume to minimize leachate changes and solubility limits during the short leachate-renewal intervals and having a small enough volume to produce measurable changes in concentrations of the leached species analyzed.

## Test Procedures

### Initial Rinse--

An initial rinse or "wash-off" of the test specimen shall be made before the actual leaching is begun. The specimen is immersed in one leachate volume (see above) for 30 seconds, then removed and placed in the leaching vessel. This initial rinse volume is analyzed for all constituents of interest. The analytical results are presented in the report section.

### Changing the Leaching Medium--

The following procedure should be followed at the end of each leaching interval. The leachate should be removed from the leaching vessel, divided into necessary aliquots and preserved for analysis. The leachate should be stirred to suspend any particulates before sample splits are made since the analyses to be made should include particulate as well as dissolved materials. Precipitation which occurs in the leachate during the leaching interval must also be included in the analyses. The leachate should not be filtered to remove particulates. In some cases, the leachate will have to be acidified to make representative samples.

The leaching vessel (but not the test sample) should be rinsed in demineralized water to remove all traces of the previous leachate. The test specimen should be exposed to the air for as short a time as possible; in no case shall its surface be allow to dry. The leaching medium (demineralized water) for the next leach interval is then added and the apparatus left for the next time interval. The leachate is not agitated or stirred during the leaching interval.

An alternative method which may be employed if practical is to remove the test specimen from the leaching vessel and to quickly place it in a new, freshly rinsed leaching vessel. Care should be taken to not scar or scratch the specimen surface (or to drop it) during the operation. In all cases the leachate should be preserved and analyzed as soon as possible.

### Leachate Replacement Frequency--

Since the length of the time intervals between leachate renewal will affect the rate of constituent release (B-1, B-2) and therefore the diffusion coefficient found, a uniform replacement schedule is required. The leachate shall be replaced completely after cumulative leaching times of 2, 7, and 24 hours after initiation of the test. Further leachate replacements are to be made at 24 hour intervals for the next 4 days and then at 72 hour intervals for the next 9 days which completes the ULP testing for that specimen. This procedure gives 10 data points--three in the first 24 hours, 7 in the first 5 days--to evaluate the leaching characteristic of the solidified waste product. The procedure is completed in 14 days.

## B.4 ORGANIZATION AND PRESENTATION OF THE RESULTS

The results of the ULP include all of the details of the procedure as actually used so that adequate comparisons can be made with the results of ULP tests performed on other materials made by other treatment processes or at different times. The following list includes the principal information required. Items should be reported in the order that they appear below.

a. Waste description: The type and source of waste, its percent solids, and its composition in mg/kg dry solids of all constituents of interest should be presented in as much detail as practical.

b. Treatment description: The type and composition of the solidification reagents including all additives; proportion of waste solids and treatment reagents and additives in the final solid waste product (on a weight/weight basis) should be included. Any deviations from standard preparation methods must be given.

c. Test specimen preparation: The method of specimen preparation should include mold type and releasers used, or coring procedures. The shape, mass, and accurate dimensions of the actual leaching specimen, the history of the specimen between preparation and leaching including time since preparation, temperature during curing, humidity during curing and storage, container(s) used, and any other relevant information should also be reported.

d. Leaching test procedures: For each leaching interval--report time to nearest minute and date of beginning and end of interval, electrical conductivity and temperature of leachate removed and of the new leaching medium. The volume of leaching medium used, and treatment of aliquots made up and preserved for analysis must be reported.

e. Integrity of test specimen: Appearance of the surface of the specimen before and after leaching; observed changes in shape or dimensions, and nature and description of any particulates or precipitates in the leachate must be included in the formal test results.

f. Analytical results: Tables must be prepared that include the concentration (in mg/ℓ) of each constituent of interest (see below) present in each leachate sample including the initial rinse, the amount of each constituent in each leachate sample (multiply the concentration in mg/ℓ times leachate volume in ℓ to give mass in mg), the fraction of the constituent present in the test specimen which has been leached in each sample, and the accumulated mass and fraction leached in the composite leachate samples and in the initial rinse, and the accumulated masses corrected for the volume-to-surface area ratio for comparison purposes, $(\Sigma A_n/A_o)(V/S)$.

g. Diffusion coefficient (effective diffusivity): The diffusion coefficient ($D_e$) as computed by any of the methods and equations given above, or any description of the variation in $D_e$ if no single value can be logically calculated must be presented in the test results.

## B.5 INTERPRETATION OF RESULTS OF ULP

After the initial removal of mobile surface constituents in the rinse procedure, the early leach rates observed with solidified waste products most often fit kinetics best explained by internal diffusion within the solid matrix. Other mechanisms such as erosion, spalling, corrosion, or dissolution are not usually important until longer leaching periods have elapsed. Until about 20% of a leachable species has been lost from a uniform, regular shaped solid, its leaching behavior when diffusion controlled approximates that for a semi-infinite medium (B-1).

The mean value of the 10 diffusion coefficients ($D_e$) calculated from the 10 leaching intervals (Equation 4, above) is the experimental value best describing the leaching properties of the waste solid. Ranges in values calculated for the diffusion coefficient using this technique which are greater than about 25% are considered to be excessive. In cases where variation of $D_e$ is large, another specimen should be tested or other explanations, such as solubility limitations or high initial values, be pursued. Another test of the validity of the data set can be made by comparing the mean of the first five $D_e$ values with the mean of the last five values; if these means vary more than about 5%, the data should be considered as biased and further tests made to verify the bias.

If single-parameter diffusion is the only leaching mechanism, the solidified waste is homogeneous and stable over the test period, then the diffusion coefficient has specific meaning. Using it, the rate of loss of the constituent in question can be predicted from large waste form under similar conditions and long-term movement of the constituent in the waste mass can be estimated. However, these theoretically derived models of simple, internal diffusion hold exactly only when:

a. The leaching medium is continuously moving and does not change in composition or character significantly.

b. The solidified waste material is homogenous and remains chemically and physically unchanged, and its surface is smooth and does not deteriorate with time.

c. The leachable species is rapidly mobilized by the leaching medium so that bulk diffusion is the limiting process.

d. No chemical interactions between the leaching species and the leaching medium, the matrix, or other leaching constituents occur.

e. The leaching species is present in but one chemical and physical form.

Surface irregularities and roughness, swelling, fissuring, surface deterioration, and chemical or physical breakdown of the matrix material all will increase the rate of loss of the leaching species. Irregular or stagnant leachate flow which allows build up of the concentration of the leaching species in the leaching medium, curing or chemical changes which influence the diffusivity in the matrix, or the presence of inhomogeneous portions of the matrix all tend to retard the leaching loss. The effective diffusivity should be considered a purely material property of the waste solid like density or heat capacity. Knowledge of its value is important to the prediction of the leaching properties of the waste solid, but its use required judgment and a thorough knowledge of other parameters of the waste material and the environment to which it will be subjected.

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# GLOSSARY

NOTE: The following terms are defined as in the Environmental Protection Agency, Rules and Regulations: Hazardous Waste Management System which appeared in the Federal Register on May 19, 1980; Vol 45, pages 33073-33076.

Definitions of terms not officially published in EPA regulations but germane to this manual (such as solidification, fixation, etc.) are discussed in Section 1.2.

aquifer: a geologic formation, group of formations, or part of a formation capable of yielding a significant amount of groundwater to wells or springs.

confined aquifer: an aquifer bounded above and below by impermeable beds or by beds of distinctly lower permeability than that of the aquifer itself; an aquifer containing confined groundwater.

container: any portable device in which a material is stored, transported, treated, disposed of, or otherwise handled.

contingency plan: a document setting out an organized, planned, and coordinated course of action to be followed in case of a fire, explosion, or release of hazardous waste or hazardous waste constituents which could threaten human health or the environment.

designated facility: a hazardous waste treatment, storage, or disposal facility which has recieved an EPA permit (or a facility with interim status) in accordance with the requirements of 40 CFR Parts 122 and 124, or a permit from a State authorized in accordance with Part 123.

dike: an embankment or ridge of either natural or man-made materials used to prevent the movement of liquids, sludges, solids, or other materials.

discharge (or hazardous waste discharge): the accidental or intentional spilling, leaking, pumping, pouring, emitting, emptying, or dumping of hazardous waste into or on any land or water.

disposal: the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including ground waters.

disposal facility: a facility or part of a facility at which hazardous waste is intentionally placed into or on any land or water, and at which waste will remain after closure.

existing hazardous waste management facility: a facility which was in operation, or for which construction had commenced, on or before October 21, 1976. Construction had commenced if:

(i) The owner or operator has obtained all necessary Federal, State, and local preconstruction approvals or permits; and either

(ii)(a) A continuous physical, on-site construction program has begun, or

(b) The owner or operator has entered into contractual obligations--which cannot be cancelled or modified without substantial loss-for construction of the facility to be completed within a reasonable time.

facility: all contiguous land, and structures, other appurtenances, and improvements on the land, used for treating, storing, or disposing of hazardous waste. A facility may consist of several treatment, storage, or disposal operational units (e.g., one or more landfills, surface impoundments, or combinations of them).

food-chain crops: tobacco, crops grown for human consumption, and crops grown for feed for animals whose products are consumed by humans.

freeboard: the vertical distance between the top of a tank or surface impoundment dike, and the surface of the waste contained therein.

free liquids: liquids which readily separate from the solid portion of a waste under ambient temperature and pressure.

generator: any person, by site, whose act or process produces hazardous waste identified or listed in EPA regulations.

groundwater: water below the land surface in a zone of saturation.

incinerator: an enclosed device using controlled flame combustion, the primary purpose of which is to thermally break down hazardous waste. Examples of incinerators are rotary kiln, fluidized bed, and liquid injection incinerators.

incompatible waste: a hazardous waste which is unsuitable for:

(i) Placement in a particular device or facility because it may cause corrosion or decay of containment materials (e.g., container inner liners or tank walls); or

(ii) Commingling with another waste or material under uncontrolled conditions because the commingling might produce heat or pressure, fire or explosion, violent reaction, toxic dusts, mists, fumes, or gases, or flammable fumes or gases.

individual generation site: the contiguous site at or on which one or more hazardous wastes are generated. An individual generation site, such as a large manufacturing plant, may have one or more sources hazardous waste but is considered a single or individual generation site if the site or property is contiguous.

in operation: refers to a facility which is treating, storing, or disposing of hazardous waste.

injection well: a well into which fluids are injected. (See also "underground injection.")

inner liner: a continuous layer of material placed inside a tank or container which protects the construction materials of the tank or container from the contained waste or reagents used to treat the waste.

landfill: a disposal facility or part of a facility where hazardous waste is place in or on land and which is not a land treatment facility, a surface impoundment, or an injection well.

landfill cell: a discrete volume of a hazardous waste landfill which uses a liner to provide isolation of wastes from adjacent cells or wastes. Examples of landfill cells are trenches and pits.

land treatment facility: a facility or part of a facility at which hazardous waste is applied onto or incorporated into the soil surface; such facilities are disposal facilities if the waste will remain after closure.

leachate: any liquid, including any suspended components in the liquid, that has percolated through or drained from hazardous waste.

liner: a continuous layer of natural or man-made materials, beneath or on the sides of a surface impoundment, landfill, or landfill cell, which restricts the downward or lateral escape of hazardous waste, hazardous waste constituents, or leachate.

hazardous waste management: the systematic control of the collection, source separation, storage, transportation, processing, treatment, recovery, and disposal of hazardous waste.

manifest: the shipping document originated and signed by the generator which contains the information required by EPA regulations.

manifest document number: the serially increasing number assigned to the manifest by the generator for recording and reporting purposes.

mining overburden returned to the mine site: any material overlying an economic mineral deposit which is removed to gain access to that deposit and is then used for reclamation of a surface mine.

movement: that hazardous waste transported to a facility in an individual vehicle.

new hazardous waste management facility: a facility which began operation, or for which construction commenced after October 21, 1976. (See also "Existing hazardous waste management facility.")

on-site: the same or geographically contiguous property which may be divided by public or private right-of-way, provided the entrance and exit between the properties is at a cross-roads intersection, and access is by crossing as opposed to going along, the right-of-way. Non-contiguous properties owned by the same person but connected by a right-of-way which he controls and to which the public does not have access, is also considered on-site property.

open burning: the combustion of any material without the following characteristics:

(i) Control of combustion air to maintain adequate temperature for efficient combustion.

(ii) Containment of the combustion-reaction in an enclosed device to provide sufficient residence time and mixing for complete combustion, and

(iii) Control of emission of the gaseous combustion products.

(See also "incineration" and "thermal treatment.")

operator: the person responsible for the overall operation of a facility.

owner: the person who owns a facility or part of a facility.

personnel (or facility personnel): all persons who work at, or oversee the operations of, a hazardous waste facility, and whose actions may result in noncompliance.

pile: any noncontainerized accumulation of solid, nonflowing hazardous waste that is used for treatment or storage.

point source: any discernible, confined, and discrete conveyance, including, but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged. This term does not include return flows from irrigated agriculture.

**publicly owned treatment works (or POTW):** any device or system used in the treatment (including recycling and reclamation) of municipal sewage or industrial wastes of a liquid nature which is owned by a State or municipality. This definition included sewers, pipes, or other conveyances only if they convey wastewater to a POTW providing treatment.

**representative sample:** a sample of a universe or whole (e.g., waste pile, lagoon, ground water) which can be expected to exhibit the average properties of the universe or whole.

**run-off:** any rainwater, leachate, or other liquid that drains over land from any part of a facility.

**run-on:** any rainwater, leachate, or other liquid that drains over land onto any part of a facility.

**saturated zone (or "zone of saturation"):** that part of the earth's crust in which all voids are filled with water.

**sludge:** any solid, semisolid, or liquid waste generated from a municipal, commercial, or industrial wastewater treatment plant, water supply treatment plant, or air pollution control facility exclusive of the treated effluent from a wastewater treatment plant.

**storage:** the holdings of hazardous waste for a temporary period, at the end of which the hazardous waste is treated, disposed of, or stored elsewhere.

**surface impoundment (or impoundment):** a facility or part of a facility which is a natural topographic depression, man-made excavation, or diked area formed primarily of earthen materials (although it may be lined with man-made materials), which is designed to hold an accumulation of liquid wastes or wastes containing free liquids, and which is not an injection well. Examples of surface impoundments are holding, storage, settling, and aeration pits, ponds, and lagoons.

**tank:** a stationary device, designed to contain an accumulation of hazardous waste which is constructed primarily of non-earthen materials (e.g., wood, concrete, steel, plastic) which provide structural support.

**thermal treatment:** the treatment of hazardous waste in a device which uses elevated temperatures as the primary means to change the chemical, physical, or biological character or composition of the hazardous waste. Examples of thermal treatment processes are incineration, molten salt, pyrolysis, calcination, wet air oxidation, and microwave discharge. (See also "incinerator" and "open burning.")

**totally enclosed treatment facility:** a facility for the treatment of hazardous waste which is directly connected to an industrial production process and which is constructed and operated [illegible] a manner which prevents the release of any hazardous waste or any constituent thereof into the environment during treatment. An example is a pipe in which waste acid is neutralized.

transportation: the movement of hazardous waste by air, rail, highway, or water.

transporter: a person engaged in the offsite transportation of hazardous waste by air, rail, highway, or water.

treatment: any method, technique, or process, including neutralization, designed to change the physical, chemical, or biological character or composition of any hazardous waste so as to neutralize such waste, or so as to recover energy or material resources from the waste, or so as to render such waste non-hazardous, or less hazardous; safer to transport, store, or dispose of; or amenable for recovery, amenable for storage, or reduced in volume.

underground injection: the subsurface emplacement of fluids through a bored, drilled or driven well; or through a dug well, where the depth of the dug well is greater than the largest surface dimension. (See also "injection well.")

unsaturated zone (or zone of aeration): the zone between the land surface and the water table.

well: any shaft or pit dug or bored into the earth, generally of a cylindrical form, and often walled with bricks or tubing to prevent the earth from caving in.

## TECHNICAL REPORT DATA

*(Please read Instructions on the reverse before completing)*

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16. ABSTRACT

Stabilization/solidification of industrial waste is a pretreatment process that has been proposed to insure safe disposal of waste containing harmful materials. This manual examines the regulatory considerations, current and proposed technology, testing procedures and design of landfills, and other options involved in disposal systems using stabilization/solidification of wastes. A summary of the major physical and chemical properties of treated waste is presented. A listing of major suppliers of stabilization/solidification technology and a summary each processess is included.

17. KEY WORDS AND DOCUMENT ANALYSIS

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